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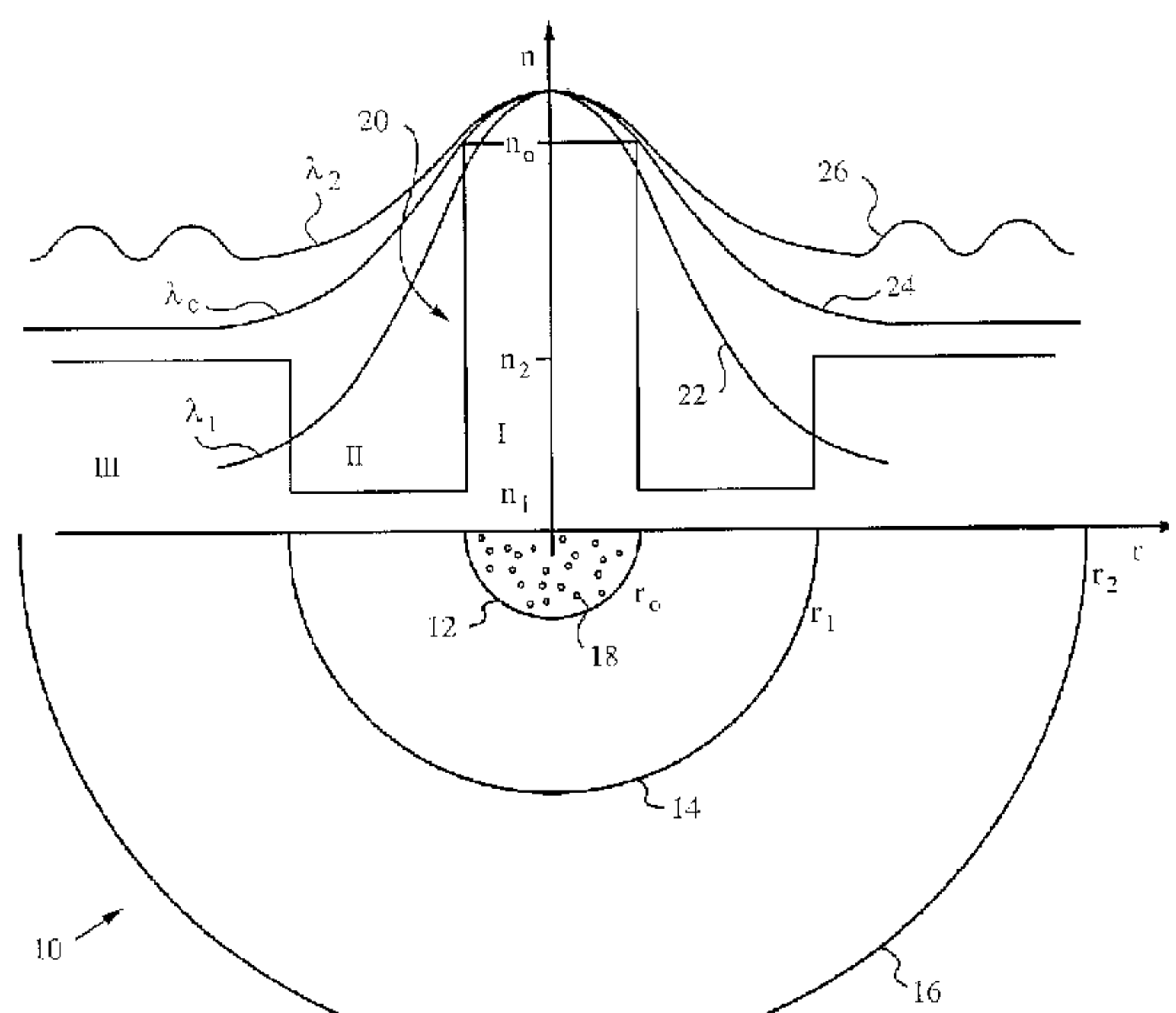
(54) Titre : AMPLIFICATEURS ET SOURCES LUMINEUSES A FIBRE DOPEE A L'ERBIUM EN BANDE S ET A FIBRE DOPEE AU THULIUM EN BANDE L A ELIMINATION REPARTIE D'EMISSION SPONTANEE AMPLIFIEE (ASE)

(54) Title: AMPLIFIERS AND LIGHT SOURCES EMPLOYING S-BAND ERBIUM-DOPED FIBER AND L-BAND THULIUM-DOPED FIBER WITH DISTRIBUTED SUPPRESSION OF AMPLIFIED SPONTANEOUS EMISSION (ASE)



(57) Abrégé/Abstract:
The present invention provides an Erbium-Doped Fiber Amplifier (EDFA) and a source that employs the EDFA for generating light in an S-band of wavelengths. A fiber amplifier (10) in a depressed cladding or W-profile fiber has a core (12) doped with the active material (18) and defined by a core cross-section and a refractive index n_0. A depressed cladding (14) of index n_1 surrounds the core (12) and a secondary cladding (16) of index n_2 surrounding the depressed cladding (14). The fiber amplifier is pumped a level of high relative inversion D, such that the active material exhibits positive gains in a short wavelength band and high gains in a long wavelength band. In one embodiment, the core cross-section, the depressed cladding cross-section and the refractive indices n_0, n_1, and n_2 are selected to provide distributed ASE suppression at wavelengths longer than cutoff wavelength λ_c over the length of fiber amplifier (10). In another embodiment, such selection provides a roll-off loss curve about a cutoff wavelength λ_c. The roll-off loss curve yields losses at least comparable to the high gains in the long wavelength band and losses substantially smaller than the positive gains in the short wavelength band. To obtain the desired roll-off loss curve the refractive index n_0 in the core is selected such that an effective index n_{eff} experienced by the confined mode maximizes a roll-off slope of the roll-off loss curve before the cutoff wavelength.

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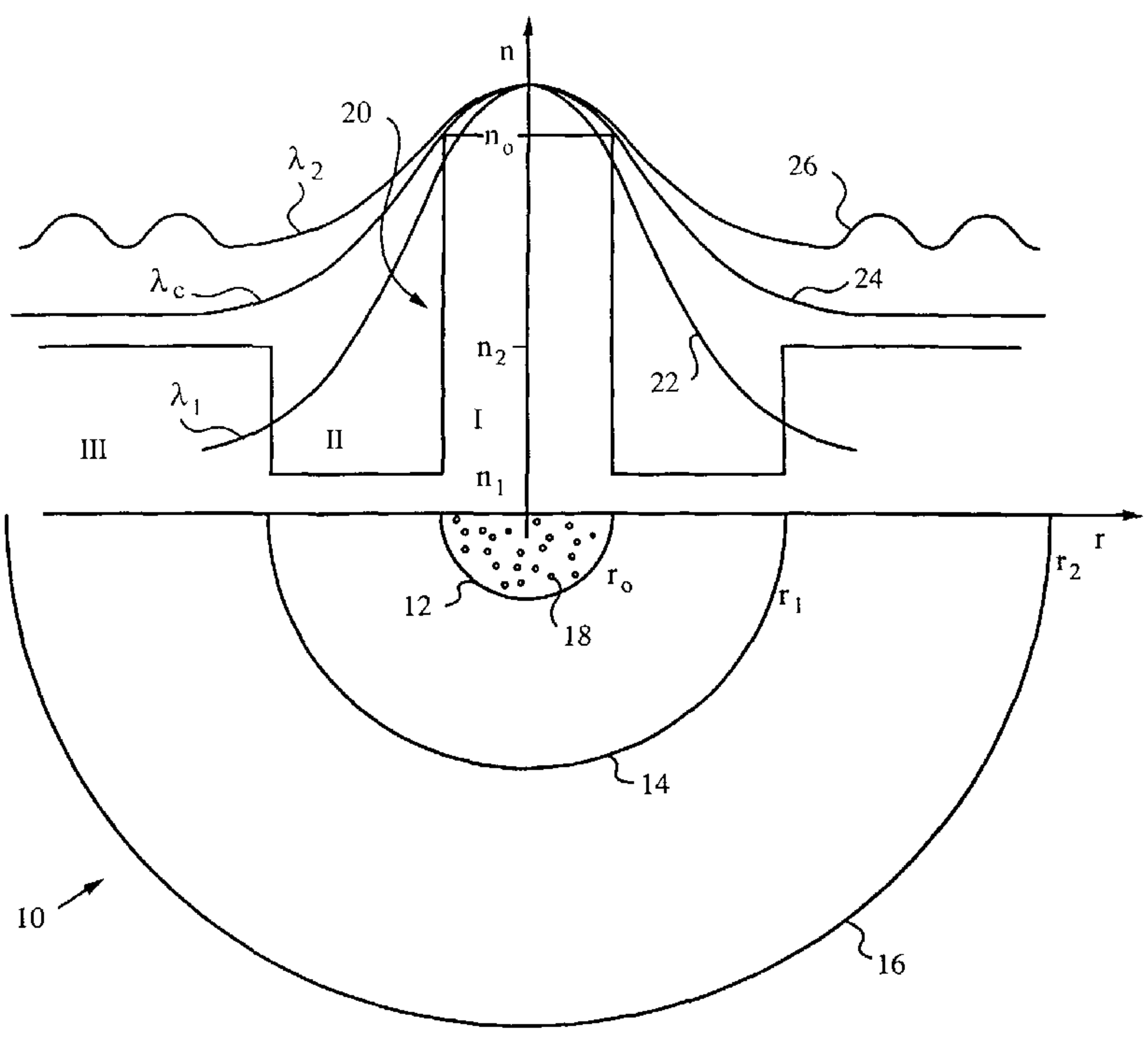

(57) Abstract: The present invention provides an Erbium-Doped Fiber Amplifier (EDFA) and a source that employs the EDFA for generating light in an S-band of wavelengths. A fiber amplifier (10) in a depressed cladding or W-profile fiber has a core (12) doped with the active material (18) and defined by a core cross-section and a refractive index n_o. A depressed cladding (14) of index n_1 surrounds the core (12) and a secondary cladding (16) of index n_2 surrounding the depressed cladding (14). The fiber amplifier is pumped a level of high relative inversion D, such that the active material exhibits positive gains in a short wavelength band and high gains in a long wavelength band. In one embodiment, the core cross-section, the depressed cladding cross-section and the refractive indices n_o, n_1, and n_2 are selected to provide distributed ASE suppression at wavelengths longer than cutoff wavelength λ_c over the length of fiber amplifier (10). In another embodiment, such selection provides a roll-off loss curve about a cutoff wavelength λ_c. The roll-off loss curve yields losses at least comparable to the high gains in the long wavelength band and losses substantially smaller than the positive gains in the short wavelength band. To obtain the desired roll-off loss curve the refractive index n_o in the core is selected such that an effective index n_{eff} experienced by the confined mode maximizes a roll-off slope of the roll-off loss curve before the cutoff wavelength.

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Amplifiers and Light Sources Employing S-Band Erbium-Doped Fiber and L-band Thulium-Doped Fiber with Distributed Suppression of Amplified Spontaneous Emission (ASE)

RELATED APPLICATIONS

This application is related to U.S. Application numbers 09/825,148, filed 2 April 2001, 10/095,303, filed 8 March 2002, 10/163,557, filed 5 June 2002, 10/194,680, filed 12 July 2002, and 10/348,802, filed 21 January 2003.

FIELD OF THE INVENTION

The present invention relates generally to fiber amplifiers with a W-profile, and in particular to S-band Er-doped fiber amplifiers with depressed cladding and distributed suppression of amplified spontaneous emissions (ASE) in the C- and L-bands, to a Tm-doped fiber amplifier for amplification in the L-band, to a method for fabricating such fibers, to a method for designing such fiber amplifiers, and to light sources employing such fiber amplifiers for producing broadband and narrowband light in the S-band.

BACKGROUND OF THE INVENTION

Optical waveguides are designed to guide light of various modes and polarization states contained within a range of wavelengths in a controlled fashion. Single-mode optical fiber is the most common waveguide for long-distance delivery of light. Other waveguides, such as diffused waveguides, ion-exchanged waveguides, strip-loaded waveguides, planar waveguides, and polymer waveguides are commonly used for guiding light over short distances and especially for combining or separating light of different wavelengths, optical frequency mixing in nonlinear optical materials, modulating light and integrating many functions and operations into a small space.

In essence, a waveguide is a high refractive index material, usually referred to as the core in an optical fiber, immersed in a lower index material or structure, usually referred to as the cladding, such that light injected into the high index material within an acceptance cone is generally confined to propagate through it. The confinement is achieved because at the interface between the high and low index materials the light undergoes total internal reflection (TIR) back into the high index material.

The performance of fiber amplifiers depends on a number of parameters including pumping efficiency, level of population inversion of the ions in the active core, amplified spontaneous emission (ASE) competing with the useful amplified signal, cross-sections and refractive indices of the active core and of the cladding surrounding the active core. In many fiber amplifiers ASE is a major obstacle to effective amplification of the desired signal and thus ASE has to be suppressed.

The problem of amplifying optical signals for long distance transmission was successfully addressed by the development of Erbium doped fiber amplifiers (EDFAs). An EDFA consists of a length of silica fiber with the core doped with ionized atoms (Er^{3+}) of the rare earth element Erbium. The fiber is pumped with a laser at a wavelength of 980 nm or 1480 nm. The doped, pumped fiber is optically coupled with the transmission fiber so that the input signal is combined with the pump signal in the doped fiber. An isolator is generally needed at the input and/or output to prevent reflections that would convert the amplifier into a laser. Early EDFAs could provide 30 to 40 dB of gain in C-band extending between 1530 to 1565 nm with noise figures of less than 5 dB. Recently, EDFAs have been developed that can provide 25 dB of gain in the L-band (1565 to 1625 nm) as well as in the C-band.

There is great interest in the telecommunications industry to make use of the optical spectrum range with wavelengths shorter than those currently achievable with conventional C-band and L-band EDFAs. This wavelength range, commonly called the "S-band" or "short-band" is poorly defined because there is no consensus on the preferred amplifier technology. In general, however, the S-band is considered to cover wavelengths between about 1425 nm and about 1525 nm.

The gain in the S-band typically observed in EDFAs is limited by several factors, including incomplete inversion of the active Erbium ions and by amplified spontaneous emissions (ASE) or lasing from the high gain peak near 1530 nm. Unfortunately, at present no efficient mechanism exist for suppressing ASE at 1530 nm and longer wavelengths in an EDFA.

Most waveguides are designed to prevent injected light from coupling out via mechanisms such as evanescent wave out-coupling (tunneling), scattering, bending losses and leaky-mode losses. A general study of these mechanisms can be found in the literature such as L.G. Cohen *et al.*, "Radiating Leaky-Mode Losses in Single-Mode Lightguides with Depressed-Index Claddings", IEEE Journal of Quantum Electronics, Vol. QE-18, No. 10, October 1982, pp. 1467-72. In this reference the authors describe the propagation of light in more complex lightguides with claddings having a variation in the refractive index also referred to as depressed-clad fibers.

L.G. Cohen *et al.* teach that varying the cladding profile can improve various quality parameters of the guided modes while simultaneously maintaining low losses. Moreover, they observe that depressed-index claddings produce high losses to the fundamental mode at long wavelengths. Further, they determine that W-profile fibers with high index core, low index inner cladding and intermediate index outer cladding have a certain cutoff wavelength above which fundamental mode losses from the core escalate. These losses do not produce very high attenuation rates and, in fact, the authors study the guiding behavior of the fiber near this cutoff wavelength to suggest ways of reducing losses.

U.S. Pat. Nos. 5,892,615 and 6,118,575 teach the use of W-profile fibers similar to those described by L.G. Cohen, or QC fibers to suppress unwanted frequencies and thus achieve higher output power in a cladding pumped laser. Such fibers naturally leak light at long wavelengths, as discussed above, and are more sensitive to bending than other fibers. In fact, when bent the curvature spoils the W or QC fiber's ability to guide light by total internal reflection. The longer the wavelength, the deeper its evanescent field penetrates out of the core of the fiber, and the more likely the light at that wavelength will be lost from the core of the bent fiber. Hence, bending the fiber cuts off the unpreferred lower frequencies (longer wavelengths), such as the Raman scattered wavelengths, at rates of hundreds of dB per meter.

Unfortunately, the bending of profiled fibers is not a very controllable and reproducible manner of achieving well-defined cutoff losses. To achieve a particular curvature the fiber has to be bent, e.g., by winding it around a spool at just the right radius. Different fibers manufactured at different times exhibit variation in their refractive index profiles as well as core and cladding thicknesses. Therefore, the right radius of curvature for the fibers will differ from fiber to fiber. Hence, this approach to obtaining high attenuation rates is not practical in manufacturing.

Moreover, the relatively high absorption losses and low gains over the S-band render the selection of fiber and fiber profile in producing an EDFA that amplifies signals in the S-band very difficult. In fact, the problems are so severe that the prior art teaches interposition of external filters between EDFA sections to produce an S-band EDFA.

For example, Ishikawa *et al.* disclose a method of fabricating an S-band EDFA by cascading five stages of silica-based EDFA and four ASE suppressing filters in Ishikawa *et al.*, "Novel 1500 nm-Band EDFA with discrete Raman Amplifier", ECOC-2001, Post Deadline Paper. In Ishikawa *et al.*'s experimental setup, the length of each EDA is 4.5 meters. The absorption of each suppressing filter at 1.53 μm is about 30 dB and the insertion losses of each suppressing filter at 1.48 μm and 0.98 μm are about 2 dB and 1 dB respectively. The pumping configuration is bi-directional, using a 0.98 μm wavelength to keep a high population inversion of more than $D \geq 0.7$ (D refers to relative inversion). The forward and backward pumping powers are the same and the total pumping power is 480 mW. Ishikawa *et al.* show a maximum gain of 25 dB at 1518.7 nm with 9 dB gain tilt.

In a similar vein, U.S. Pat. No. 5,260,823 to Payne *et al.* teaches an EDFA with shaped spectral gain using gain-shaping filters. The inventors take advantage of the fact that the EDFA is distributed to interpose a number of the gain-shaping filters along the length of the EDFA, rather than just placing one filter at the end of the fiber. Yet another example of an approach using a number of filters at discrete locations in a wide band optical amplifier is taught by Srivastava *et al.* in U.S. Pat. No. 6,049,417. In this approach, the amplifier employs a split-band architecture where the optical signal is split into several independent sub-bands, which then pass in parallel through separate branches of the optical amplifier. The amplification performance of each branch is optimized for the sub-band which traverses it.

Unfortunately, these prior methods are complicated and not cost-effective, as they require a number of filters. Specifically, in the case of Ishikawa *et al.*, five EDFAs, four ASE suppressing filters, and high pump power are required. Also, each of the ASE suppressing filters used by either method introduces an additional insertion loss of 1-2 dB. The total additional insertion loss is thus about 4-8 dB.

Another approach to providing amplification in the S-band has focused on fiber amplifiers using Thulium as the lasing medium doped into a Fluoride fiber core (TDFAs). See, for example, "Gain-Shifted Dual-Wavelength-Pumped Thulium-Doped-Fiber Amplifier for WDM Signals in the 1.48-1.51-μm Wavelength Region" by Tadashi Kasamatsu, et. al., in IEEE Photonics Technology Letters, Vol. 13, No. 1, January 2001, pg. 31-33 and references therein. While good optical performance has been obtained using TDFAs, this performance has only been possible using complex, non-standard and/or expensive pumping schemes. Also, TDFAs suffer from the problems inherent to their Fluoride fiber host material, namely high fiber cost, poor reliability and difficulty splicing to standard silica fibers used elsewhere in the amplifier system.

Still other approaches to producing amplification systems based on rare-earth doped fiber amplifiers and cascaded amplifiers or pre-amplifiers followed by amplifiers are described in U.S. Patents 5,867,305; 5,933,271 and 6,081,369 to Waarts *et al.* and in U.S. Patent 5,696,782 to Harter *et al.* The teachings in these patents focus on deriving high peak power pulses at high energy levels. The amplifiers described in these patents are not suitable for producing broadband and narrowband sources for the S-band.

In view of the aforementioned difficulties in obtaining high attenuation rates in W-profile fibers as well as the selection of fiber and fiber profile in producing an EDFA that amplifies signals in the S-band, more recent prior art teaches distributed suppression of ASE at wavelengths longer than a cutoff wavelength in fiber amplifiers such as EDFAs. This is achieved by engineering fiber parameters including the index profile and cross sections of the core and cladding layer including the use of a W-profile refractive index. The approach is discussed in more detail in the above-referenced U.S. Patent Application 10/095,303.

Although effective in suppressing ASE at wavelengths longer than the cutoff wavelength, the EDFA's cross-section enables the coupling of radiation at wavelengths below the cutoff wavelength between the core and the cladding. This effect, also known as cladding mode resonance, produces artifacts or cladding mode coupling losses in the short wavelength range of interest where the signal is to be amplified. For a general discussion of cladding mode coupling losses the reader is referred to Akira Tomita *et al.*, "Mode Coupling Loss in Single-Mode Fibers with Depressed Inner Cladding", Journal of

Lightwave Technology, Vol. LT-1, No. 3, September 1983, pp. 449-452.

Cladding mode loss is a problem encountered in fiber Bragg gratings. One solution is to extend a photosensitive region in the core beyond the core to suppress cladding mode losses as taught in U.S. Pat. No. 6,351,588 to Bhatia *et al.* entitled "Fiber Bragg Grating with Cladding Mode Suppression". U.S. Pat. No. 6,009,222 to Dong *et al.* also teaches to take advantage of a W-profile refractive index to confine the core mode and cladding modes thus reducing their overlap and coupling. Related alternatives to confining the core mode to suppress cladding mode losses are found in U.S. Pat. No. 5,852,690 to Haggans *et al.* and U.S. Pat. No. 6,005,999 to Singh *et al.*

Unfortunately, the approaches which are useful in suppressing cladding mode losses and avoiding cladding mode resonance in fiber Bragg gratings can not be applied to fiber amplifiers. That is because of fundamental differences in fabrication, construction and operating parameters between fiber Bragg gratings and fiber amplifiers with distributed suppression of ASE.

Clearly, there is a need for a fiber amplifier with distributed suppression of ASE at wavelengths longer than a cutoff wavelength that is able to suppress cladding mode resonance or the coupling of radiation between the core and cladding at wavelengths shorter than the cutoff wavelength. It would be particularly useful to provide an EDFA having these capabilities where the wavelengths below the cutoff wavelength are contained in the S-band. Moreover, it would be an advance in the art to provide a fiber amplifier exhibiting net gains over the S-band with low pump power and without requiring external filters. In particular, it would be an advance to provide an EDFA with distributed ASE suppression in the C-band and L-band or substantially at 1530 nm and longer wavelengths over the whole length of a fiber amplifier. It would be also a welcome advance in the art to provide a method of designing such fiber amplifiers with net gain over the S-band as well as reliable narrowband and broadband light sources employing such fiber amplifiers that can be used for testing optical components, measuring the performance of optical components and generating signals in the S-band.

OBJECTS AND ADVANTAGES

It is a primary object of the present invention to provide a fiber amplifier that yields losses exceeding any high gains in a long wavelength band and at the same time yields losses substantially smaller than any positive gains in a short wavelength band. In particular, it is an object of the invention to provide an Er-doped fiber amplifier (EDFA) in which the long wavelength band is the C-band and L-band and the short wavelength band is the S-band. More specifically, the EDFA is to provide suppression of amplified spontaneous emission (ASE) near 1525 nm and above and ensure positive gains of at least 15 dB over the S-band.

It is an object of the invention to provide such fiber amplifier in a W-profile (or depressed cladding) fiber and use the fiber's index profile to eliminate the need for external filters and reduce the required pump power by controlling a roll-off loss curve.

It is another object of the present invention to provide a fiber amplifier with distributed suppression of amplified spontaneous emissions (ASE) above a certain cutoff wavelength and suppression of cladding mode loss at wavelengths shorter than the cutoff wavelength. In particular, it is an object of the invention to provide an Erbium-doped fiber amplifier having these capabilities.

It is a further object of the invention to provide short-pass fibers that use a depressed cladding geometry to define a cutoff wavelength and an associated roll-off loss curve. In particular, the invention provides a reliable method for drawing fibers that contain various types of dopants, including active materials such as rare earth ions.

It is another object of the invention to provide reliable narrowband and broadband light sources in the S-band of wavelengths with Er-doped fibers or Erbium-doped fiber amplifiers (EDFAs).

It is yet another object of the invention to provide a Thulium-doped silica fiber having its strongest gain at a range from about 1.6 μm to about 1.7 μm.

These and numerous other advantages of the present invention will become apparent upon reading the following description.

SUMMARY

The objects and advantages of the invention are achieved by a source generating light in an S-band of wavelengths using a W-profile fiber having a core doped with an active material such as Neodymium, Erbium or Thulium ions. The fiber core has a certain cross section and a refractive index n_o. An active material or lasant is doped into the core for amplifying light, e.g., any information-bearing light beam. The fiber's core is surrounded by a depressed cladding having a depressed cladding cross-section and a refractive index n_1. Furthermore, the fiber has a secondary cladding surrounding the depressed cladding. The secondary cladding has a secondary cladding cross-section and a refractive index n_2. In an embodiment, a pump source is provided for pumping the Erbium contained in the core to a high relative inversion D, such that the Erbium exhibits positive gains in the S-band and high gains in a long wavelength band longer than the S-band. The core cross-section, the depressed cladding cross-section, and the refractive indices n_o, n_1, and n_2 are selected to produce losses at least comparable to the high gains in the long wavelength band and losses substantially smaller than the positive gains in the S-band.

In another embodiment, the core cross-section, the depressed cladding cross-section and the refractive indices n_o, n_1, and n_2 are selected to obtain a roll-off loss curve about a cutoff wavelength λ_c. The roll-off loss curve yields losses at least comparable to the high gains in the long wavelength band and losses substantially smaller than the positive gains in the short wavelength band.

In order to obtain the desired roll-off loss curve the refractive index n_o in the core is selected such that an effective index n_{eff} experienced by a mode of radiation which is guided, e.g., the fundamental mode at wavelength shorter than the cutoff wavelength, is large. In particular, refractive index n_o is selected such that the slope of the effective index n_{eff} experienced by the confined mode is maximized, thereby maximizing a roll-off slope of the roll-off loss curve before the cutoff wavelength λ_c. Preferably, the refractive index n_o is selected such that the slope of the effective index n_{eff} is in the range of .002/100nm to .008/1000nm. In another preferred embodiment, the refractive index n_o of the core is chosen such that the roll-off slope of the roll-off loss curve is greater than or about equal to the maximum slope of the gain spectrum. In this embodiment, it is possible to select a cutoff wavelength such that the distributed loss exceeds the gain for all wavelengths in the long wavelength band, but that the gain exceeds the distributed loss for all wavelengths in the short wavelength band.

Depending on the design of the roll-off loss curve, the cutoff wavelength λ_c can be contained in the long wavelength band or in the short wavelength band, or between the short and long wavelength bands.

It is important that the selection of the cross-sections, i.e., the radii, and the selection of indices of refraction be not performed merely to establish a ratio of radii or refractive indices, but to fix absolute differences between them. Thus, it is preferable that the refractive index n_o of the core differ from the refractive index n_2 of the secondary cladding by about 0.005 to about 0.03. Also, the refractive index n_1 of the depressed cladding should differ from the refractive index n_2 of the secondary cladding by about -0.004 to about -0.02.

In the preferred embodiment the fiber amplifier uses Er as the active material, i.e., it is an Er-doped fiber amplifier (EDFA) doped with a concentration of 0.1% wt. of Er. In this case it is further preferred that the short wavelength band is selected to be at least a portion of the S-band and the long wavelength band is selected to be at least a portion of the C-band and/or L-band. Further, it is advantageous to set the cutoff wavelength λ_c near 1525 nm in this embodiment. The host material used by the fiber amplifier is preferably a silicate-containing glass such as alumino-germanosilicate glass or phosphorus doped germanosilicate glass.

The pump source providing the pump radiation to invert the population in the Er ions can be any suitable pump source. For example, the pump source is a laser diode emitting pump radiation at about 980 nm. Alternative sources delivering pump radiation at about 980 nm can also be used. It is preferred that pumping is in-core pumping.

The fiber amplifier of the invention can be used in fibers of various cross-sectional profiles. For example, the core-cross section can have the shape of a circle, an ellipse, a polygon or another more complex shape. The same is true for the depressed cladding cross-section. The circular cross-sections can be used if no preferential polarization is to be amplified by the fiber amplifier. The eliptical cross-section can be used when a particular polarization is to be maintained during amplification over an orthogonal polarization.

For proper operation of the fiber amplifier it is important that the pump source provide pump radiation at a sufficient intensity to ensure a high relative inversion D, specifically $D \geq 0.7$. This is especially important in the preferred embodiment where the active material is Er.

Fiber amplifiers designed in accordance with the invention can be used in any situation where high gains are produced in a long wavelength band adjacent a short wavelength band in which the signal to be amplified is contained. In these situations the ASE from the long wavelength band will tend to prevent amplification of signals in the short wavelength band, especially when the positive gains in the short wavelength band are low in comparison to the high gains in the adjacent long wavelength band. The design is particularly useful in EDFAs to amplify signals in the short wavelength S-band. For this purpose the cutoff wavelength λ_c is preferably set at 1525 nm and the roll-off loss curve is selected to yield losses of at least 100 dB in the C-band and L-band to suppress ASE from the 1530 nm gain peak. Meanwhile, the roll-off loss curve is also adjusted to yield losses in the S-band which are smaller by at least 5 dB than the positive gains in the S-band to allow for signal amplification. This relationship will ensure at least a 5 dB amplification in the S-band.

In accordance with another embodiment of the invention several fiber amplifiers made according to the method can be used to amplify signals in the short wavelength band, e.g., the S-band. The length L of each of the fiber amplifiers can be varied to obtain the desired amount of gain for separate portions of the S-band.

In some embodiments the arrangement for suppressing coupling between the active core and the cladding is a material distributed in the cladding. The material can be a scattering material or an absorbing material. For example, a rare earth element can be used as the absorbing material.

Preferably, the cladding has a depressed cladding having a depressed cladding cross-section and a refractive index n_1 and a secondary cladding having a secondary cladding cross-section and a refractive index n_2. The scattering or absorbing material is distributed in the secondary cladding. The radiation propagating in the active core occupies a mode having a mode diameter. The mode diameter extends from the active core into the cladding. It is important that the material be distributed outside the mode diameter of the radiation.

In some embodiments the arrangement for suppressing coupling between the active core and the cladding is a non-phase-matched length section in the fiber amplifier. The non-phase-matched length section is built such that coupling of the radiation between the active core and the cladding is not phase matched. In these embodiments the core has a core cross-section and a refractive index n_o and the cladding has a cladding cross-section and a refractive index n_{clad}. The non-phase-matched length section is formed by a predetermined selection of the core cross-section, cladding cross-section and refractive indices n_o, n_{clad}. Preferably, the cladding has a depressed cladding having a depressed cladding cross-section and refractive index n_1, a secondary cladding having a secondary cladding cross-section and a refractive index n_2. The non-phase-matched length section is formed by a predetermined selection of the cross-sections and refractive indices n_o, n_1, n_2. Even more preferably, the cladding has an outer cladding having an outer cladding cross-section and a refractive index n_3 and n_3 is selected such that $n_3<n_2$.

The fiber amplifier can contain any suitable active medium in its active core. For example, the active core can be doped with Neodymium, Erbium, or Thulium ions. When using Erbium, the fiber amplifier is an EDFA and in one advantageous embodiment its cutoff wavelength λ_c is set near 1525 nm. Thus, the EDFA is pumped by a pump source delivering radiation at a pump wavelength near 980 nm. Under these conditions the

EDFA can be used for amplifying signals in the short wavelength range falling within the S-band.

In another example, Thulium is doped into fused-silica fibers. Although the Thulium gain is typically thought to be at 1.9 microns, and indeed that is the peak of the gain, the wavelength range over which gain is possible stretches from 1.5 microns to 2.1 microns. The typical Thulium pump wavelength is 0.78 microns. However, it is also possible to pump Thulium at 1.48 microns, though very high intensities would be needed, possibly as high as 100 mW. 100mW at 1.48 microns is easily obtainable with commercially available high quality diode pumps with about 500mW at 1480nm and nearby wavelengths. Another good pump wavelength is 1530nm where high power sources, up to Watts, are available.

The gain cross-section and the upper-laser-level lifetime of the Thulium ion are similar to those of the Erbium ion which is conventionally used to make 1.5 micron amplifiers. Thus the threshold for gain is similar - several milliwatts of pump power are required.

The Thulium ion could be used on the short-wavelength end of its gain region in exactly the same way as the Erbium ion. By pumping with an intense pump (30 mW or so) it is possible to reach inversion even at short wavelengths. However, before high gain is reached at a short wavelength such as 1.6 microns, there will be overwhelming superfluorescence near 1.9 microns.

A useful amplifier can be made at the shorter wavelength if the fiber is designed with a fundamental mode cut-off between 1.9 microns and the shorter wavelength of desired operation, and if the cut-off is such that the increase in loss at longer wavelengths exceeds the increase in gain due to the higher cross-section. This technique makes it possible to build useful amplifiers in the wavelength range between about 1.6 to 1.8 microns. Since telecommunication fiber is highly transmissive in this range, it is anticipated that amplifiers that work in this wavelength range will be highly desirable.

In accordance with the invention fiber amplifiers can be designed to suppress cladding mode loss. This is done in fibers where an appropriate index profile in the active core and cladding is established to set a cutoff wavelength λ_c. Cutoff wavelength λ_c is set such that the fiber amplifier exhibits positive gains in a short wavelength range below the cutoff wavelength λ_c. The coupling of radiation in the short wavelength range between the core and cladding is suppressed. This is achieved by distributing a material that scatters or absorbs the radiation in the cladding of the fiber amplifier. Preferably, the material is located outside the mode diameter of the radiation propagating through the active core. In another embodiment, the coupling is suppressed by preventing phase matching such that the coupling of radiation between the core and cladding is not phase matched. This can be achieved by engineering the cross-sections and refractive indices of the core and cladding in accordance with the invention.

When using the source as a narrowband source a wavelength selecting mechanism is provided for selecting an output wavelength of the light. This mechanism can be a feedback mechanism such as a fiber Bragg grating. In other embodiments the wavelength selecting mechanism is a filter selected from the group consisting of tilted etalons, strain-tuned fiber Bragg gratings, temperature-tuned fiber Bragg gratings, interferometers, arrays waveguide gratings, diffraction gratings and tunable coupled cavity reflectors. Alternatively, or in combination with the feedback mechanism or filter an additional pump source adjustment for tuning the high relative inversion D can be used to select the output wavelength. In yet another alternative, or in combination with the previous mechanism or mechanisms, a coiling diameter of the fiber can be used to select the output wavelength. The coiling diameter can be constant or variable, e.g., it can be continuously variable.

The fiber of the source can be placed within an optical cavity, e.g., in cases where it is desired that the fiber operate as a laser for producing light at a specific narrow output wavelength. Preferably the cavity is a ring cavity.

In one embodiment of the source, a master oscillator is used for seeding the fiber. The master oscillator can be any suitable optical source such as a distributed feedback laser, a Fabry-Perot laser, an external cavity diode laser, a distributed Bragg reflector laser, a vertical cavity surface emitting laser, a semiconductor laser, a fiber laser or a broadband source.

In a preferred embodiment, the fiber is broken up into two sections. The first section of the fiber has a first coiling diameter and the second section has a second coiling diameter larger than the first coiling diameter. The first section, whose emission spectrum is centered at a shorter wavelength, is positioned before the second section whose emission spectrum is centered at a longer wavelength. In this configuration the output from the first section is used to seed the second section. In some embodiments an isolator is installed between the two sections.

In another embodiment the first section is designed such that the core cross-section, the depressed cladding cross-section, and the refractive indices n_o, n_1, and n_2 produce a first cutoff wavelength λ_{c1}. Meanwhile, the core cross-section, the depressed cladding cross-section, and the refractive indices n_o, n_1, and n_2 in the second section are designed to produce a second cutoff wavelength λ_{c2} that is longer than the first cutoff wavelength λ_{c1}. In this embodiment the first section produces an emission spectrum centered at a shorter wavelength and the second section produces an emission spectrum centered at a longer wavelength. Once again, the first section is positioned before the second section for seeding the second section. An isolator can be installed between the two sections in this embodiment.

The pump source for pumping the Erbium in the core of the fiber is preferably a laser diode. For example, one can use a laser diode providing pump light at about 980 nm. In accordance with the method of the instant invention it is preferable to use a counter-propagating pumping arrangement to pump the Erbium. In other words, the pump light is counter-propagating with respect to the output light.

The source of the invention can be used for testing and measuring purposes as well as for generating output light in the S-band. The source can be operated in a continuous mode or in a pulsed mode, as desired. The output light generated by the fiber can also be combined with light outside the S-band, e.g., with light in the C- and L-bands.

A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1 is a diagram illustrating a W-profile fiber and guided and unguided modes according to the invention.

Fig. 2 is a graph illustrating a typical index profile in the fiber of Fig. 1.

Fig. 3 is a graph illustrating the selection of appropriate core index n_o to ensure that the effective index experienced by a guided mode in the short wavelength band of interest is maximized.

Fig. 4 is a graph illustrating appropriate selection of the core index to obtain a suitable roll-off loss curve in an Er-doped fiber amplifier (EDFA) in accordance with the invention.

Fig. 5 is a graph of the absorption and gain cross sections of Er ions in alumino-germanosilicate glass.

Fig. 6 is an isometric view of an EDFA operated in accordance with the invention.

Fig. 7 are graphs of net gain in a 6 meter long alumino-germanosilicate EDFA doped at 0.1% wt. with a mode overlap factor Γ=0.5 at various inversion values D.

Fig. 8 are graphs of net gain spectra in an alumino-germanosilicate EDFA at inversion values between D=0.4 and D=1 for fiber lengths between 5 meters and 13 meters chosen to maintain 45 dB gain at 1530 nm.

Fig. 9 are graphs of gain spectra for a 15 meter long alumino-germanosilicate EDFA at inversion values between D=0.6 and D=1.

Fig. 10 is a diagram illustrating the use of three EDFA amplifiers to amplify three portions of the S-band.

Fig. 11 is a graph illustrating the gain spectra for the three EDFAs of Fig. 10

Fig. 12 illustrates the cross-section of another fiber amplifier with an elliptical core and depressed cladding.

Fig. 13 is a diagram illustrating a partial cross-section of a fiber amplifier in accordance with the invention and illustrating a core mode and a cladding mode.

Fig. 14 is a graph illustrating a typical index profile in the fiber of Fig. 13.

Fig. 15 is a graph illustrating the effects of cladding mode losses in the fiber of Fig. 13.

Fig. 16 are graphs illustrating the effects of an absorbing polymer material embedded in outer cladding of the fiber of Fig. 13.

Fig. 17 is a diagram illustrating a partial cross-section of another fiber amplifier according to the invention.

Fig. 18 is a graph illustrating the phase-matching condition between core modes and cladding modes in the fiber amplifier of Fig. 17.

Fig. 19 are graphs of power levels of radiation in core mode and cladding mode.

Figs. 20A&B are graphs illustrating the effective index n_{eff} experienced by the core mode and cladding modes.

Figs. 21A&B are cross-sectional view of alternative fiber amplifiers in accordance with the invention.

Fig. 22 is a diagram illustrating the use of an EDFA in a fixed narrowband source according to the invention.

Fig. 23 is a graph illustrating the typical shaped of the ASE emission spectrum of the EDFA used in the source of Fig. 22.

Fig. 24 is a diagram illustrating the use of an EDFA in an alternative source according to the invention.

Fig. 25 is a diagram illustrating a source using a single EDFA in a ring cavity.

Fig. 26 is a diagram illustrating a source using two EDFAs in a parallel configuration in a ring cavity.

Fig. 27 is a diagram illustrating a source using an EDFA's coiling diameter for output wavelength tuning.

Fig. 28 is a diagram illustrating a source using two fiber sections in accordance with the invention.

Fig. 29 is a graph illustrating the effects of seeding EDFA having a longer wavelength emission spectrum by an EDFA having a shorter wavelength emission spectrum.

Fig. 30 is a graph illustrating the ASE emission spectra for EDFAs at several coiling diameters.

Fig. 31 is a graph illustrating the effect of using different pump power levels in two EDFA sections separated by an isolator on the total ASE emission spectrum.

Fig. 32 is a diagram of a source with two EDFAs having different coiling diameters separated by an isolator.

Fig. 33 is a diagram of a source with two EDFAs having different coiling diameters and employing a single pump source.

Fig. 34 is a diagram illustrating an S-band source using a master oscillator.

Fig. 35 is a diagram illustrating the use of an S-band source in a testing or measuring application in accordance with the invention.

Fig. 36 is a diagram illustrating the pulling of a preform into a short-pass fiber with a depressed-profile.

Fig. 37A is a graph illustrating the transverse portion of the refractive index profile in the preform of Fig. 36.

Fig. 37B is a graph illustrating the longitudinal portion of the refractive index profile in the preform of Fig. 36.

Fig. 38 are graphs of exemplary roll-off loss curves obtained with the method of the invention.

Fig. 39 shows the fluorescence spectrum of Thulium in fused silica.

DETAILED DESCRIPTION

The instant invention will be best understood by first reviewing the principles of generating a roll-off loss curve in a depressed profile or W-profile fiber **10** as illustrated in Figs. 1-4. Fig. 1 is a diagram illustrating a portion of a cross-section of a fiber **10** having a core **12** surrounded by a depressed cladding **14.** Depressed cladding **14** is surrounded by a secondary cladding **16.** Core **12** has a circular cross-section, as do depressed cladding **14** and secondary cladding **16.** A region **I** associated with core **12** extends from $0 \le r \le r_0$, depressed cladding **14** and secondary cladding **16** occupy regions **II, III** extending between $r_o \le r \le r_1$ and $r \ge r_1$. Core **12** has an index of refraction n_o, depressed cladding **14** has an index of refraction n_1 and secondary cladding **16** has an index of refraction n_2. The graph positioned above the partial cross-section of fiber **10** illustrates an average index profile **20** defining a W-profile in fiber **10.** In the present embodiment fiber **10** is a single mode fiber.

Fiber **10** has an active material **18** doped in core **12.** Active material **18** is a lasing medium such as a rare earth ion or any other lasant which exhibits high gains in a long wavelength band and positive gains in a short wavelength band. Specifically, when pumped to a high relative inversion D, the high gains of active material **18** in the long wavelength band cause amplified spontaneous emissions (ASE) or lasing which reduces the population inversion of lasant **18** and thus reduces the positive gains in the short wavelength band, making it impossible to effectively amplify signals in the short wavelength band.

Fig. 2 illustrates a W-profile **20A** as is obtained with normal manufacturing techniques. For the purposes of the invention it is sufficient that the radially varying index of core **12** have an average value equal to n_o. Likewise, it is sufficient that indices of depressed cladding **14** and secondary cladding **16** average out to the values n_1 and n_2. The average index n_o of core **12** is significantly higher than index n_1 of depressed cladding **14** and index n_2 of secondary cladding **16**. The selection of appropriate values of indices n_o, n_1, n_2 and radii r_o, r_1, r_2 is made to achieve certain guiding properties of fiber **10**, as required by the instant invention. Specifically, profile **20** is engineered to have a fundamental mode cutoff wavelength λ_c such that light in the fundamental mode at wavelengths smaller than λ_c is retained in core **12** while light in fundamental mode at wavelength λ_c or longer wavelengths is lost to secondary cladding **16** over a short distance. This objective is accomplished by appropriately engineering W-profile **20A**.

Fundamental mode cutoff wavelength λ_c of fiber **10** is a wavelength at which the fundamental mode (the LP_{01} mode) transitions from low-losses to high losses in core **12**, i.e., is cut off from core **12**. First, the fundamental mode cutoff wavelength λ_c for fiber **10** is set in accordance to selection rules for cross-sections and refractive indices n_o, n_1 and n_2 of fiber **10** as derived from Maxwell's equations. In the weak guiding approximation (which is valid when the indices of refraction of core **12** and claddings **14, 16** are all relatively close to each other), the Maxwell vector equations can be replaced with a scalar equation. The scalar ψ represents the strength of the transverse electric field in the fiber. For more information, see for example G. Agrawal, "Nonlinear Fiber Optics" (Academic, San Diego, 1995), D. Marcuse, "Light Transmission Optics" (Van Nostrand, Princeton, 1972), and D. Marcuse, "Theory of Dielectric Optical Waveguides" (Academic, New York, 1974).

For convenience, let us define the following parameters:

$$u_0 = \sqrt{n_0^2 - n_2^2} \quad \text{and} \quad u_1 = \sqrt{n_2^2 - n_1^2} \qquad (1)$$

The scalar field ψ inside fiber **10** satisfies a wave equation whose solutions are Bessel functions and modified Bessel functions. For the fundamental mode supported by fiber **10**, inside core **12** is thus:

$$\psi = J_0(\kappa r), \quad 0 \le r \le r_0 \text{ (region I)} \qquad (2)$$

where κ is an eigenvalue that needs to be determined, and J_0 is the zeroth Bessel's function.

Inside depressed cladding **14**, the scalar field ψ is:

$$\psi = A K_0(\beta r) + B I_0(\beta r), \quad r_0 \le r \le r_1 \text{ (region II)} \qquad (3)$$

where A and B are constants to be determined, $\beta^2 = (u_0^2 + u_1^2)(2\pi/\lambda)^2 - \kappa^2$, and K_0 and I_0 are the modified Bessel's functions. Here λ is the vacuum wavelength of the light.

In secondary cladding **16**, we obtain:

$$\psi = C K_0(\gamma r), \quad r \ge r_1 \text{ (region III)} \qquad (4)$$

Here C is another constant, and $\gamma^2 = u_0^2(2\pi/\lambda)^2 - \kappa^2$. A, B, C, and κ are found using the boundary conditions, which require that ψ and its first derivative are both continuous at r_0 and r_1.

It can be shown that fundamental mode cutoff wavelength λ_c is a wavelength λ at which $\gamma = 0$. (See for example, Cohen et al., IEEE J. Quant. Electron. QE-18 (1982) 1467-1472.)

For additional convenience, let us define the following parameters:

$$x = \frac{2\pi\, u_0 r_0}{\lambda_c}, \qquad \rho = u_1/u_0, \qquad s = r_1/r_0. \qquad (5)$$

Now, fundamental mode cutoff wavelength λ_c can be determined if parameter x is determined. That determination can be made with the aid of algebra known to a person skilled in the art, since parameter x is the root of the following equation:

$$\rho\, J_0(x)\, K_1(\rho x)\, I_1(\rho s x) - \rho\, J_0(x)\, I_1(\rho x)\, K_1(\rho s x) - J_1(x)\, K_1(\rho s x) I_0(\rho x) - J_1(x)\, I_1(\rho s x)\, K_0(\rho x) = 0. \qquad (6)$$

Three observations should be made regarding the parameter x. First, x does not exist for all values of s and ρ. For example, for $\rho = 1$ and $s \le \sqrt{2}$, there is no x that satisfies Eq. (6). This means that all wavelengths are guided in core **12** in this regime. The criterion that Eq. (6) have a solution is:

$$s^2 \ge 1 + 1/\rho^2. \qquad (7)$$

Second, for practical applications x cannot be too small. This is because, according to Eq. (5), the parameter x is proportional to radius r_0 of core **12**, and the radius has to be large enough that it is easy to couple light into and out of core **12**. (A smaller core **12** also makes the nonlinear effects stronger, which is often a disadvantage.) Therefore, since $x = 2\pi u_0 r_0/\lambda_c$, preferably $x \geq 1$. This implies that $\rho \geq 0.224$ or, in terms of the refractive indices $\sqrt{(n_2^2 - n_1^2)/(n_o^2 - n_2^2)} \geq 0.224$.

Third, it is evident from Fig.7 that for larger values of s, the value of x only weakly depends on s. Thus it is advantageous to have a fiber in this region of parameter space, since a manufacturing flaw producing an error in s will have a small effect on the value of fundamental mode cutoff wavelength λ_c. Therefore, it is convenient to use the rule $s \geq 1 + 1/\rho$, or in terms of the refractive indices:

$$\frac{r_1}{r_o} \geq 1 + \sqrt{(n_o^2 - n_2^2)/(n_2^2 - n_1^2)}. \qquad (8)$$

The selection of cross sections and refractive indices of core **12**, depressed cladding **14** and outer cladding **16** is guided by the above rules in setting the appropriate fundamental mode cutoff wavelength λ_c. First, λ_c can be pre-selected, e.g. a wavelength close to 1530 nm, and then convenient values are selected for u_o and r_o. Based on these choices x is computed from equation 5, and conveniently $x \geq 1$ (otherwise the previous choices can be adjusted). Then, suitable values of s and ρ are found using equation 6. A range of values for ρ and s will yield desired λ_c. Typically, all values of ρ are larger than 0.224. In addition, the rule of equation 8 is used to further narrow the range of suitable values of ρ and s.

Finally, the values of s and ρ have an additional limitation. Namely, they must be selected so that core **12** of fiber **10** has a great enough loss, e.g., 5 dB/m or even 100 dB/m or more at a wavelength $\lambda > \lambda_c$. To find the loss at wavelength $\lambda > \lambda_c$, the fiber modes for light having wavelength $\lambda > \lambda_c$ are required.

Equations (2), (3), and (4) specify the fundamental mode when $\lambda < \lambda_c$. When $\lambda > \lambda_c$, the function ψ is oscillatory, rather than exponentially decaying, in secondary cladding **16**. Therefore when $\lambda > \lambda_c$, Eq. (4) is replaced by:

$$\psi = C\ J_0(qr) + D\ N_0(qr), \qquad r \geq r_1 \text{ (region } \mathbf{III}\text{)} \quad (9)$$

where N_0 (also called Y_0) is the zeroth Neumann function, $q^2 = \kappa^2 - u_0^2(2\pi/\lambda)^2$, and C and D are constants to be determined.

There are two key items to note regarding the modes for $\lambda > \lambda_c$. First, there are five unknowns (A, B, C, D, and κ) and four boundary conditions (continuity of ψ and dψ/dr at r_0 and r_1). The equations are underconstrained: κ may be chosen to be any value between 0 and $(2\pi/\lambda)\sqrt{u_0^2 + u_1^2}$. Thus, there is a continuum of states for each $\lambda > \lambda_c$, corresponding to the continuum of values that κ may have. This situation is quite different from the case $\lambda < \lambda_c$, where four unknowns (A, B, C, and κ) are fixed by the four boundary conditions, resulting in κ being a discrete eigenvalue having a unique value at each $\lambda < \lambda_c$.

Second, the modes specified by Eqs. (2), (3), and (9) are eigenmodes of the fiber, e.g. a W-fiber; however, these modes do not correspond to the situation that is physically realized. This is a result of Eq. (9) containing both incoming and outgoing waves, whereas in practice only outgoing waves are present (the light at wavelength $\lambda > \lambda_c$ originally propagating in core **12** radiates out).

Nevertheless, the modes of Eqs. (2), (3), and (9) can be used to estimate the losses at wavelengths greater than λ_c. First, for a given wavelength λ, find the value of κ that minimizes $C^2 + D^2$. This corresponds to the mode that is the most long-lived within the core. (An analogy can be made between the wave equation for the scalar ψ in the fiber and the quantum mechanical wave equation for a particle in a potential well. Then the quantum mechanical results can be borrowed. See for example David Bohm, "Quantum Theory", Dover 1989, Chapter 12 §14 - 22.)

Second, once κ is found in the above manner, the outgoing waves can be computed from Eq. (9). These outgoing waves give a reasonable estimation of the loss from core **12** into secondary cladding **18**, even when no incoming waves are present. These outgoing waves will cause beam at wavelength $\lambda > \lambda_c$ propagating in core **12** to be attenuated along the length of the fiber. If the beam has power P, then the change in power P with distance z along fiber **10** is described by the equation:

$$\frac{dP}{dz} = -\Lambda P \quad . \qquad (10)$$

The loss is given by the coefficient Λ, which is approximately:

$$\Lambda = \frac{\lambda}{4\pi^2 n_0} \frac{C^2 + D^2}{\int_0^{r_0} r dr\, \psi^* \psi} . \qquad (11)$$

The loss Λ, having units of m^{-1}, can be converted to a loss β in units dB/m, using the relation:

$$\beta = 10\ \log_{10}(e) \cdot \Lambda\ . \qquad (12)$$

Here the term "loss" refers to radiation that leaks out of core **12** into secondary cladding **16.** In fact, the radiation may not be truly lost from fiber **10** itself, if it remains in secondary cladding **16.** In some cases this will be sufficient. In other cases light from secondary cladding **16** can be out-coupled, as necessary.

Another method for calculating the losses involves calculating the complex propagation constant of the leaky fundamental mode of fiber **10.** Leaky modes are discussed in, for example, D. Marcuse, "Theory of Dielectric Optical Waveguides" (Academic, New York, 1974) Chapter 1. The loss is related to the imaginary part of the complex propagation constant of the leaky mode. The complex propagation constant, or its equivalent that is the complex effective index of refraction, may be computed using commercially available software, such as that obtainable from Optiwave Corporation of Nepean, ON, Canada.

In some cases it may be preferable to numerically solve for the modes of a given fiber rather than use the Bessel function approach outlined above, since real fibers do not have the idealized step index profile indicated by profile **20** shown in Fig. 1, but have variations from the ideal as shown by graph **20A** in Fig. 2 of the actual refractive index profile obtained in practice. In particular, the most common method of single-mode fiber manufacture today involves the MOCVD process, which typically leaves an index dip in the center of core **12.** Numerical solutions can, more easily than the method described above, take into account the actual variations in refractive index as a function of radius. Such numerical calculations can again give fundamental mode cutoff wavelength λ_c and fiber losses as a function of fiber parameters including cross-sections and refractive indices, allowing fiber **10** to be designed to exhibit the desired features.

When Eq. (11) is used to estimate the loss, refractive indices n_0, n_1, and n_2 will in general be average indices of refraction of profile **20,** since the actual indices of refraction will vary somewhat as a function of radius (see profile **20A**). Also, the index of refraction n is not necessarily radially symmetric. If the cross section of fiber **10** is described by polar coordinates r and θ the refractive index may depend upon the angle θ as well as the radius r. Thus, $n = n(r,\theta)$. Such an asymmetric fiber may be desirable for polarization maintenance, for example.

Here is the prerequisite for the fiber to have fundamental mode cutoff wavelength λ_c. Let R be a radius large enough that the index at radius R has substantially leveled off to the value n_2. Then fiber **10** will have fundamental mode cutoff wavelength λ_c if (see B. Simon, Ann. Phys. 97 (1976), pp. 279):

$$\int_0^{2\pi} d\theta \int_0^R r dr \left(n^2(r,\theta) - n_2^2\right) \leq 0 \quad . \qquad (13)$$

Note that given the profile of Fig. 1, Eq. (13) becomes:

$$\pi\ r_0^2\ u_0^2 - \pi\ (r_1^2 - r_0^2)\ u_1^2 \leq 0, \qquad (14)$$

which is equivalent to Eq. (7) above.

Fundamental mode cutoff wavelength λ_c is the largest wavelength for which there is an eigenmode that is localized in region **I**. The losses for wavelengths above cutoff wavelength λ_c can be determined, for example, by (i) solving for the modes that are not localized but include incoming and outgoing waves, (ii) for each wavelength finding the mode with the smallest outgoing intensity, and (iii) using this outgoing intensity to estimate the loss. As discussed above, other methods are also available to a person skilled in the art for calculating losses. In general, fiber **10** with a desired fundamental mode cutoff wavelength λ_c and losses can therefore be designed by adjusting the profile $n(r,\theta)$, which is equivalent to adjusting the cross-sections and refractive indices of core **12**, depressed cladding **14** and secondary cladding **16**.

The rules presented above will enable a person skilled in the art can to set fundamental mode cutoff wavelength λ_c by making a selection of r_o, r_1, n_o, n_1 and n_2. This selection of r_o, r_1, n_o, n_1 and n_2 provide distributed ASE suppression over the length of the fiber **10** and result in a family of loss curves with different roll-offs (with respect to wavelength). Therefore, additional constraints have to be placed on the selection of r_o, r_1, n_o, n_1 and n_2 to achieve the objectives of the present invention, as discussed below.

Referring back to Fig. 1, superposed on average index profile **20** is an intensity distribution of a guided fundamental mode **22** at a first wavelength $\lambda_1<\lambda_c$. First wavelength λ_1 is contained within a short wavelength band. A fundamental mode

24 which is no longer guided by fiber **10** is also superposed on index profile **20**. Mode **24** is at cutoff wavelength λ_c. An intensity distribution of another mode **26** which is not guided by fiber **10** and exhibits an oscillating intensity distribution beyond core **12** and depressed cladding **14** is also shown. Radiation in mode **26** has a second wavelength λ_2, which is longer than cutoff wavelength $\lambda_c<\lambda_2$ and is contained in a long wavelength band.

The graphs in Fig. 3 are plots of wavelength versus an effective index n_{eff} experienced by guided mode **22** whose wavelength λ_1 is contained within a short wavelength band **42** and of non-guided mode **24** at cutoff wavelength λ_c for three choices of the value of index n_o of core **12**. Specifically, at a lowest value of index n_{o1} of core **12**, the effective index n_{eff} experienced by mode **22** is described by graph **28**. Graph **28** illustrates a relatively low value of effective index n_{eff} over short wavelength band **42**, i.e., over the entire range of wavelengths λ_1 at which mode **22** is guided. In addition, the value of n_{eff} remains very low in a region of interest **40** below cutoff wavelength λ_c. The choice of an intermediate value of index n_{o2} of core **12** produces graph **30**. In this graph n_{eff} is higher than in graph **28** over the entire short wavelength band **42**. Still, the value of n_{eff} is low in region of interest **40**. A choice of a large value of index n_{o3} produces graph **32**, which increases n_{eff} experienced by mode **22** over entire short wavelength band **42** including region of interest **40**. Given such large value of refractive index n_{o3} effective index n_{eff} exhibits a large negative slope right before cutoff wavelength λ_c in region of interest **40**. Preferably, the value of refractive index n_{o3} is large enough such that this roll-off slope is in the range of .002/1000 nm to .008/1000 nm. In a preferred embodiment, the refractive index n_o of the core is at least 0.5% larger than the refractive index n_2 of the secondary cladding. Of course, a person skilled in the art will realize that index n_o of core **12** can not be made arbitrarily large to continue increasing the negative slope of n_{eff} before λ_c due to material constraints.

Fig. 4 illustrates a gain profile **44** of active material **18** when pumped to a high relative inversion D. Short wavelength band is designated by reference **42**, as in Fig. 3, and long wavelength band is designated by reference **46**. Gain profile **44** exhibits high gains in long wavelength band **46** and positive gains in short wavelength band **42**. In particular, high gains in long wavelength band **46** include a peak **48** very close to short wavelength band **42**.

In this embodiment the cross-sections or radii of core **12**, depressed cladding **14** and refractive indices n_o, n_1, and n_2 are selected to place cutoff wavelength λ_c right at peak **48**. Additionally, the value of index n_o of core **12** is selected to obtain a roll-off loss curve **38** about cutoff wavelength λ_c set at peak **48** of high gains in long wavelength band **46**. More particularly, roll-off loss curve **38** is selected to yield losses at least comparable to the high gains in long wavelength band **46** while yielding losses substantially smaller than the positive gains in short wavelength band **42**. Roll-off loss curve **38** drops below the positive gains indicated by profile **44** because of its rapid decrease or large positive slope to the left for wavelengths below cutoff wavelength λ_c. The gains thus exceed losses across entire short wavelength band **42**, as better visualized by hatched area **50**. Preferably, roll-off loss curve **38** is such that the gains exceed the losses in short wavelength band **42** by at least 5 dB.

Curve **38** is obtained when n_{eff} experienced by guided mode **22** is high and the slope of n_{eff} just below λ_c has a large negative slope. In other words, curve **38** is obtained by selecting index n_{o3} for core **12.** Roll-off loss curves obtained with lower indices n_{o2} and n_{o1} in core **12** are indicated by references **36** and **34** respectively. Because n_{eff} and its slope below λ_c experienced by mode **22** can not be maximized by choosing indices lower than n_{o3}, the roll-off slope is smaller for curves **36** and **34** and thus the losses they introduce in short wavelength band **42** remain above the positive gains. As long as losses exceed gains no useful amplification can be produced by active material **18** in short wavelength band **42.**

The W-profile fiber designed in accordance with the above rules finds its preferred embodiment when active material **18** is Er and the short wavelength band is the S-band or a select portion of the S-band while the long wavelength band covers the C-band and/or the L-band or a select portion or portions of these two bands. Preferably, the host material of fiber **10** is silicate-containing glass such as alumino-germanosilicate glass or phosphorus doped germanosilicate glass.

Fig. 5 shows the wavelength dependent absorption cross-section **60** and wavelength dependent emission cross section **62** of Er-doped alumino-germanosilicate glass. Other Er-doped glasses have qualitatively similar gain (emission) and absorption spectra. Note that the gain extends to wavelengths shorter than 1450 nm, but the absorption cross section is much greater than the emission cross section for all wavelengths with a short wavelength band **64,** in this case the S-band extending from about 1425 nm to about 1525 nm. Specifically, absorption cross section is much above emission cross section near 1500 nm. This indicates that high levels of relative population inversion D is required for Er to yield substantial net gain in S-band **64.** A long wavelength band **66,** in this case the C-band and the L-band extend from 1525 nm to 1600 nm and beyond. The C- and L-bands exhibit high gains, especially in the C-band at a peak wavelength of about 1530 nm. The choice of alumino-germanosilicate glass or phosphorus doped germanosilicate glass is preferred because when Er is doped into these host materials the emission cross section is increased in comparison to standard glass fiber. Other glass compositions which boost the emission cross section in S-band **64** relative to emission cross section **62** at the emission peak near 1530 nm can also be used.

Fig. 6 shows an Er-doped fiber amplifier **68** (EDFA) using alumino-germanosilicate glass as the host material. EDFA **68** is doped with a concentration of 0.1% wt. of Er in a core **70** of index n_o. Core **70** is surrounded by a depressed cladding **72** of index n_1 and a secondary cladding **74** of index n_2. EDFA **68** has a protective jacket **76** surrounding secondary cladding **74** to offer mechanical stability and to protect EDFA **68** against external influences.

A signal radiation **78** at a first wavelength λ_1 contained within S-band **64** is delivered to EDFA **68** for amplification from a fiber **80.** For example, signal radiation **78** can be an information-bearing signal requiring amplification.

Fiber **80** is coupled with a fiber **82** in a wavelength combiner **84.** Fiber **82** is used to couple a pump radiation **88** from a pump source **86** to EDFA **68.** Pump source **86,** preferably a laser diode, provides pump radiation **88** at a pump wavelength λ_p of about 980 nm for pumping the Er ions in core **70** to achieve a high level of relative population inversion D. Parameter D varies from D=-1 indicating no population inversion to D=1 signifying complete population inversion. When D=0, exactly half of the Er ions are in the excited energy state or manifold of states, while half remain in the ground energy manifold. In this case, EDFA **68** is approximately transparent (for wavelengths near the 3-level transition at 1530 nm). For non-uniformly inverted EDFAs, parameter D is considered as the average value of inversion. In the present embodiment, the intensity of pump radiation **88** is determined such that it ensures a relative inversion of $D \geq 0.7$ in the Er ions.

Pump radiation **88** and signal radiation **78** are combined in combiner **84** and both delivered to EDFA **68** by fiber **90**. More particularly, both signal and pump radiation **78**, **88** are coupled into core **70** from fiber **90**.

Core **70** and claddings **72**, **74** all have circular cross sections in this embodiment. The cross sections and indices n_o, n_1, n_2 are selected in accordance with the method of invention to set cutoff wavelength λ_c near 1525 nm (see Fig. 5). In other words, cutoff wavelength λ_c is selected to be between short wavelength band **64** or the S-band and the long wavelength band **66** or the C-band and L-band.

It is important that index n_o of core **70** be chosen to provide for a large negative slope in effective index n_{eff}, preferably about .008/1,000 nm, near cutoff wavelength λ_c. As a result, the roll-off loss curve exhibits a rapid decrease for wavelengths below cutoff wavelength λ_c ensuring that the losses in S-band **64** are lower than the positive gains. The losses produced by this roll-off loss curve increase rapidly for wavelengths larger than cutoff wavelength λ_c. Thus, the losses produced in the C- and L-bands **66** are at least comparable to the high gains.

Designing EDFA **68** in accordance with the invention will ensure that signal radiation **78** at λ_1 is amplified while ASE at any wavelength λ_2 in the C- and L-bands **66,** and especially at λ_2=1530 nm is rejected into cladding **74** as shown. Positive gains in S-band **64** will typically be on the order of 25 dB above the losses and thus, to obtain sufficient amplification of signal radiation **78,** EDFA **68** requires a certain length L. The smaller the difference between the positive gains and losses in the S-band **64,** the longer length L has to be to provide for sufficient amplification of signal radiation **78.** In the present embodiment L is about 6 meters.

Fig. 7 shows the net gain (gain minus absorption) of EDFA **68** for L=6 meters and with a typical mode-overlap factor, Γ=0.5 without the benefit of the roll-off loss curve. The family of curves represent various levels of inversion, from D=0.6 through D=1. Note that as the level of inversion is increased, the net gain increases for all wavelengths. For full inversion (D=1), the S-band **64** net gain ranges from 5-25 dB over 1470-1520 nm, the C-band **66** net gain exceeds 30 dB, and the 1530 nm gain peak exhibits over 55 dB of net gain. This condition is, in practice, very difficult to achieve because lasing at 1530 nm, and/or significant amplified spontaneous emission (ASE) would occur at significantly lower values of net gain (about 45 dB or lower), thereby limiting the achievable level of inversion. The middle curve (D=0.8, with 90% of Er ions in the excited energy manifold) corresponds approximately to this ASE-limited situation, with about 25 dB of net gain within the C-band **66** and only about 10 dB of net gain within the S-band **64.**

In prior art EDFAs this situation gets worse (for the S-band) when a C-band EDFA is optimized for efficiency (dB gain per unit pump power). This optimization results in somewhat longer (or more highly doped) fibers which become ASE-limited (45 dB net gain at 1530 nm) with lower levels of inversion. In summary, most EDFAs in use today operate with incomplete inversion because of 1530 nm-ASE combined with the requirement for good overall efficiency.

The relationship between the level of inversion, D, and the net gain in the S-band **64** relative to the net gain in the C-band **66** is shown in Fig. 8. A family of curves representing the net gain spectra for EDFA **68** without the benefit of the roll-off loss curve at inversion levels between D=0.4 and D=1, and L between 5 meters and 13 meters is shown. Lengths L were chosen in order to maintain 45 dB of net gain at 1530 nm, as this situation corresponds approximately to the onset of ASE. Note that the higher levels of inversion D favor gain in S-band **64**, while more moderate (D=0.4-0.6) levels of inversion result in minimal gain-slope within the C-band **66**. In other words, an EDFA designed for use within the S-band **64** should have nearly complete inversion, unlike an EDFA optimized for use within the C-band **66**. For this reason, in the preferred embodiment the invention is maintained in the range D≥0.7.

Referring still to Fig. 8, one observes that the gain in S-band **64** can not exceed ~5 dB at 1470 nm and ~20 dB at 1520 nm if the 1530 nm gain is limited to 45 dB. To achieve higher gain the length L of EDFA **68** has to be increased, while maintaining a high level of inversion would to produce larger gain in S-band **64**. Fig. 9 shows the net gain spectra for EDFA **68** at inversion levels between D=0.6 and D=1, when length L is increased to 15 meters. While gain in S-band **64** exceeds 20 dB for a bandwidth exceeding 30 nm, the 1530 nm gain is in excess of >100 dB for D>0.7. Now, with the aid of the roll-off loss curve engineered in EDFA **68** in accordance with the invention, the losses at 1530 nm can be comparable or larger than this gain, thus preventing ASE or lasing.

Fig. 10 illustrates an embodiment in which three EDFAs **102, 104, 106** doped with Er at 0.1% wt. all engineered in accordance with the invention are provided to amplify three portions of the S-band. Four wavelength combiners **108, 110, 112, 114** are used to connect EDFAs **102, 104, 106** in accordance with well-known splicing and wavelength combining procedures to separately amplify the three portions of the S-band. EDFA **102** has a length of 10 meters and a cutoff wavelength λ_c at 1520 nm, EDFA **104** has a length of 33 meters and a cutoff wavelength λ_c at 1490 nm, and EDFA **106** has a length of 143 meters with a cutoff wavelength λ_c at 1460 nm. EDFA **102** amplifies input in the 1490-1520 nm range, EDFA **104** amplifies input in the 1460-1485 nm range and EDFA **106** amplifies input in the 1435-1455 nm range. All EDFAs **102, 104, 106** are engineered for the largest possible slope of n_{eff}, i.e., .008/1000 nm, near their respective cutoff wavelengths and the indices of refraction are: n_o=+0.011 and n_1=-0.0053. Fig. 11 illustrates the net gain spectra for these three EDFAs when pumping is sufficiently strong to obtain an inversion D=0.9. Note that they cover about 80 nm of total bandwidth in the S-band and provide gain exceeding 15 dB over this 80 nm bandwidth.

It should be noted that cutoff wavelength in this embodiment is placed in the short wavelength band for EDFAs **104** and **106**. In fact, cutoff wavelength can also be placed in the long wavelength band, if desired. The choice of exactly where to place the cutoff wavelength can be made by the designer once the slope of the roll-off is known and the amount of high gains in the long wavelength band to be matched or exceeded are known.

Fiber amplifiers according to the invention can be used in fibers whose cores and cladding layers have cross-sections other than circular. For example, Fig. 12 illustrates the cross-section of a fiber amplifier **120** engineered according to the invention and whose core **122** is elliptical. Depressed cladding **124** is also elliptical while secondary cladding **126** has a circular cross section. These elliptical cross sections are advantageous when radiation in one polarization rather than the other polarization is to be maintained during amplification.

Fig. 13 is a diagram illustrating a partial cross-section of a fiber amplifier **210** with a core mode and a cladding mode. The fiber amplifier **210** has an active core **212** surrounded by a depressed cladding **214**, which is surrounded by a secondary cladding **216**. Core **212** as a circular cross section, as do depressed cladding **214** and secondary cladding **216**. In addition, an outer cladding **220** of circular cross-section surrounds secondary cladding **216**.

A region **I** associated with core **212** extends from $0 \leq r \leq r_0$, while depressed cladding **214** and secondary cladding **216** occupy regions **II**, **III** extending between $r_o \leq r \leq r_1$ and $r_1 \leq r \leq r_2$. Outer cladding **220** is associated with a region **IV** extending from $r > r_2$. Core **212** has an index of refraction n_o, depressed cladding **214** has an index of refraction n_1 and secondary cladding **216** has an index of refraction n_2. Outer cladding

220 has an index of refraction n_3. The graph positioned above the partial cross-section of fiber amplifier **210** illustrates an average index profile **222** defined in fiber amplifier **210.** In the present embodiment fiber amplifier **210** is a single mode fiber amplifier.

Fiber amplifier **210** has an active material **218** doped in core **212.** Active material **218** is a lasing medium such as a rare earth ion or any other lasant that exhibits high gains in a long wavelength band and positive gains in a short wavelength band. Specifically, when pumped to a high relative inversion D, the high gains of active material **218** in the long wavelength band cause amplified spontaneous emissions (ASE) or lasing which reduces the population inversion of lasant **218** and thus reduces the positive gains in the short wavelength band.

Superposed on average index profile **222** is an intensity distribution of radiation in a guided fundamental core mode **224** at a first wavelength λ_1 where $\lambda_1<\lambda_c$. First wavelength λ_1 is contained within a short wavelength band where active material **218** exhibits positive gains. An intensity distribution of radiation in a cladding mode **226** that exhibits an oscillating intensity distribution beyond core **212** and depressed cladding **214** is also shown. There is an overlap between core mode **224** and cladding mode **226** as indicated by hatched areas **A.** However, as with all modes of waveguide structures, these modes are orthogonal (cladding mode **226** is anti-symmetric in electric field) in the ideal case. Hence, ideally there is no coupling between core mode **224** and cladding mode **226.** However, all real waveguides have imperfections, inhomogeneities, scattering centers and perturbations which break the orthogonality and enable coupling between core and cladding modes. In fact, the three main causes of coupling in fiber amplifier **210** are manufacturing defects, bending or coiling of fiber amplifier **210** as necessary for packaging purposes, and micro bends and stresses which are pre-existing (e.g., frozen in during manufacturing) or caused during packaging. Clearly, it is beneficial to reduce these causes for coupling as far as possible.

Fig. 14 illustrates a refractive index profile **222A** as is obtained with normal manufacturing techniques. For the purposes of the invention it is sufficient that the radially varying index of core **212** have an average value equal to n_o. Likewise, it is sufficient that indices of depressed cladding **214**, secondary cladding **216** and outer cladding **220** average out to the values n_1, n_2, n_3. The average index n_o of core **212** is significantly higher than index n_1 of depressed cladding **214** and index n_2 of secondary cladding **216**. In this embodiment, the average index n_3 of outer cladding **220** is higher than all other indices, although this need not be so.

The selection of appropriate values of indices n_o, n_1, n_2 and radii r_o, r_1, r_2 is made to achieve certain guiding properties of fiber amplifier **210**, as required by the instant invention. In particular, index profile **222A** is established in core **212** and in the first two cladding layers, i.e., depressed cladding layer **214** and secondary cladding layer **216** such that radiation in core **212** exhibits a loss above a cutoff wavelength λ_c and positive gains in a short wavelength range below the cutoff wavelength λ_c. In a preferred embodiment, index profile **222A** is engineered to have a fundamental mode cutoff wavelength λ_c such that radiation in fundamental mode **224** at wavelengths smaller than λ_c is retained in core **212** while radiation in fundamental mode **224** at wavelength λ_c or longer wavelengths is lost to secondary cladding **216** over a short distance. An exemplary engineering method of the refractive index profile **222A** will now be discussed.

In Fig. 13, the cutoff wavelength λ_c is set such that core **212** exhibits a loss above cutoff wavelength λ_c and positive gains due to active material **218** in a short wavelength range below the cutoff wavelength λ_c. This selection of r_o, r_1, n_o, n_1 and n_2 provides distributed ASE suppression at wavelengths longer than cutoff wavelength λ_c over the length of fiber amplifier **210**. Superposed on average index profile **222** is the intensity distribution of radiation in guided fundamental core mode **224** at a first wavelength λ_1 where $\lambda_1<\lambda_c$ and the intensity of radiation in cladding mode **226**. Radiation in core mode **224** and in cladding mode **226** propagates at first wavelength λ_1. In other words, single mode fiber amplifier **210** allows for discrete modes, such as mode **226** to propagate in secondary cladding **216**. Substantial power can then be transferred from core mode **224** to cladding modes such as cladding mode **226** when the phase velocities of core mode **224** and cladding mode **226** become identical. For a theoretical teaching on the cladding mode coupling effect the reader is referred to Akira Tomita *et al.*, "Mode Coupling Loss in Single-Mode Fibers with Depressed Inner Cladding", Journal of Lightwave Technology, Vol. LT-1, No. 3, September 1983, pp. 449-452.

The transfer of power from core mode **224** to cladding mode **226** causes losses from core **212** at wavelength λ_1. Thus, a signal at λ_1 within the short wavelength band is not able to take advantage of the full positive gains of active material **218** at λ_1. As used herein, these losses are referred to as cladding mode losses. In certain cases, some power is also transferred back from cladding mode **226** to core mode **224** when coupling exists between core mode **224** and cladding mode **226.** As used herein, this condition is referred to as cladding mode resonance.

The general effect of cladding mode losses sustained by fiber amplifier **210** is shown in Fig. 15. In this example Erbium is used as active material **18** and the short wavelength band is within the S-band. Specifically, graph **228** shows the gains of Erbium around its peak **230** at about 1530 nm. The design of refractive index profile of fiber **210** sets cutoff wavelength λ_c just below 1530 nm, e.g., at 1525 nm and produces a loss curve **232.** Loss curve **232** indicates that the losses above cutoff wavelength λ_c increase rapidly. Thus, any ASE due to the gains of Erbium at 1530 nm and at longer wavelengths is effectively suppressed. Meanwhile, in short wavelength band **234** below cutoff wavelength λ_c Erbium exhibits gains above the losses produced by loss curve **232.** In other words, the Erbium has positive gains in short wavelength band **234** and is therefore able to amplify signals in short wavelength band **234.**

Due to coupling between fundamental mode **224** and cladding mode **226** at wavelength λ_1 there is a loss peak **236** in short wavelength band **234** centered at λ_1. The size of loss peak **236** is not drawn to scale and is indicated in dashed lines. It should be noted that in practice there can be a number of wavelengths within short wavelength band **234** at which coupling between core mode and cladding mode occurs producing corresponding loss peaks. Also, it should be noted that coupling between fundamental core modes and cladding modes at wavelengths longer than λ_c can take place as well. For example, core mode and cladding mode coupling occurs at λ_2.

The corresponding cladding mode resonance **238** is indicated in dashed lines. Because ASE in the wavelength range spanning λ_2 is suppressed, this coupling is not as detrimental to the function of fiber amplifier **210**. Still, in a preferred embodiment, cladding mode coupling at wavelengths longer than λ_c should also be avoided.

Clearly, loss peak **236** reduces the effectiveness of fiber amplifier **210** at wavelength λ_1. Therefore, in accordance with the invention, loss peak **236** is suppressed by suppressing cladding mode loss in fiber amplifier **210**. In the general case, as well as in this embodiment, this object is achieved by providing an arrangement for suppressing the coupling of radiation in the short wavelength range between active core **212** and secondary cladding **216**. In the embodiment of Fig. 13, the arrangement for suppressing coupling employs a material **240** distributed in outer cladding **220**.

Material **240** is a scattering material or an absorbing material. In either case, material **240** is embedded in outer cladding **220** at a distance where core mode **224** is negligibly small. In particular, core mode **224** has a mode diameter D extending from core **212** into the cladding, i.e., into depressed cladding **214** and secondary cladding **216**. Material **240** is distributed outside the mode diameter of core mode **224**. Thus, core mode **224** does not exhibit appreciable intensity in the region where material **240** is deposited within outer cladding **220**. This means that in single mode fiber amplifier **210** material **240** should be embedded several tens of microns away from core **212**. It should be noted that outer cladding **220** can be made up entirely of material **240** if outer cladding **220** commences at a distance where core mode **224** is negligibly small.

In the embodiment where material **240** is an absorber, it can be a rare earth element doped into outer cladding **220.** Suitable materials include Erbium, Cobalt, Samarium and other suitable absorbers. Material **240** can be embedded in outer cladding **220** using any suitable fabrication technique. For example, in a typical manufacturing process employing the "sleeving technique" a sleeve of pure silica that is to be pulled over secondary cladding **216** can be provided with a layer of doped material **240** prior to the sleeving process. Specifically, a layer of doped material **240** coated onto the inner surface prior to the sleeving process can be employed. Modified Chemical Vapor Deposition (MCVD) and solution doping, followed by sintering can be used to create the proper layer of absorbing material **240.**

In another embodiment, material **240** is any suitable scattering material, such as an inhomogeneous acrylate layer or other material exhibiting rapid variations in the refractive index and/or geometry. Scattering material can employ two scattering effects. First, it can scatter radiation in cladding mode **226** that is phasematched with core mode **224** into an assortment of other cladding modes. Typically there will be a large number (usually hundreds) of other cladding modes into which radiation of cladding mode **226** can be scattered. This effect is substantially equivalent to absorption loss as far as cladding mode **226** is concerned. Alternatively, radiation in cladding mode **226** can be perturbed in phase in a random fashion by scattering material **240.** This effect is substantially similar to preventing phase matching between core mode **224** and cladding mode **226.** By preventing phase matching the accumulation of cladding mode loss over a long distance of fiber amplifier **210** is thus prevented.

The effect of using material **240** in outer cladding **220** is illustrated in Fig. 15. Specifically, by using material **240** loss peak **236** at λ_1 is reduced to a smaller loss peak **236'** indicated in solid line. Fig. 16 illustrates the experimental results of using absorbing material **240** in the form of a polymer buffer in outer cladding **220** of fiber amplifier **210**. In this case, the host material of fiber **210** is silicate-containing glass such as alumino-germanosilicate glass or phosphorus doped germanosilicate glass. Graph **242** indicates the gain experienced by a signal in fiber **210** without material **240** in outer cladding **220** and graph **244** indicates the gain obtained with material **240**. In these cases both material **240** and outer cladding **220** are made of polymer materials with differing loss characteristics. Clearly, the dip in gain associated with loss peak **236** is removed with the aid of absorbing material **240**. Thus, fiber amplifier **210** of present invention provides distributed suppression of amplified spontaneous emissions (ASE) above cutoff wavelength λ_c and suppresses cladding mode loss at wavelengths shorter than cutoff wavelength λ_c, i.e., wavelengths in short wavelength range **234** such as wavelength λ_1 in particular. It should be noted that the presence of absorbing material **240** in outer cladding **220** also suppresses cladding mode effects at λ_2.

Fig. 17 illustrates a partial cross-section of another fiber amplifier **200** in accordance with the invention. Parts of fiber amplifier **200** corresponding to those of fiber amplifier **210** are referenced by the same reference numbers. In fiber amplifier **100** the arrangement for suppressing coupling between core mode **224** and cladding mode **226** is a non-phase-matched length section of fiber amplifier **200**. In the non-phase-matched length section outer cladding **220** has a lower refractive index n_3 than all other indices. Most importantly, refractive index n_3 is lower than refractive index n_2 of secondary cladding **216**, i.e., $n_3<n_2$. This condition ensures that radiation in core mode **224** and cladding mode **226** are not phase matched. Appropriate material for outer cladding **220** to ensure such low refractive index n_3 is silicone, Teflon, Fluorine-doped silica and other low-index materials such as those used in dual clad fibers well known to those skilled in the art.

Prevention of phase matching and the selection of the value of refractive index n_3 will be better understood by referring to the graphs in Fig. 18. Graph **2102** illustrates the normalized propagation constant of radiation in core mode **224** plotted versus inverse of the wavelength (i.e., optical frequency, which is also proportional to the k-vector) for $n_3 \geq n_2$. Graph **2104** illustrates the normalized propagation constant of radiation in cladding mode **226** also plotted versus inverse of the wavelength for $n_3 \geq n_2$. (The condition $n_3 \geq n_2$ is typical for telecommunications fibers which use acrylate as the typical outer cladding also referred to as buffer.) At $1/\lambda_1$ graphs **2102** and **2104** intersect indicating phasematching and hence cladding mode loss.

Graphs **2106** and **2108** in Fig. 19 illustrate the power level of radiation normalized to the value 1 (100% power level) in core mode **224** and cladding mode **226**, respectively. Graphs **2106** and **2108** are observed for the phasematched condition and are graphed as a function of length of fiber amplifier **200** assuming an ideal case in which no power is lost or gained (i.e., no amplification). The power level of core mode **224** represented by graph **2106** starts at the high power value of 1 and undergoes sinusoidal oscillations between 1 and 0. In contrast, the power level of cladding mode **226** starts at the low power value of 0 and undergoes sinusoidal oscillation between 0 and 1. Clearly, power is transferred from core mode **224** to cladding mode **226** during the first part of the oscillation and back from the cladding mode **226** to core mode **224** during the second part of the oscillation.

In practice, outer cladding **220** has a loss of a finite value α per unit length of fiber amplifier **200** while the loss in core **212** is negligible. Therefore, the power in core mode **224** will not manage to be coupled completely into cladding mode **226**. Under these conditions, the power level in core mode **224** will follow a graph **2106′** and the power level in cladding mode **226** will follow a graph **2108′** as shown for an intermediate value of α. At a large value of α the power levels will follow graphs **2106″** and **2108″**. The cladding mode loss prevents appreciable power from building up in cladding mode **226**, thereby reducing the coupling of power from core mode **224** to cladding mode **226**. In fact, the loss of power γ from core mode **224** to cladding mode **226** can be described by the following equation:

$$\gamma = \frac{8.7c^2}{\alpha}, \qquad (15)$$

where c^2 is the speed of light squared. From this equation it is evident that increasing the loss α experienced by cladding mode **226** decreases the loss experienced by core mode **224**. For a detailed derivation of the equation the reader is referred to Akira Tomita *et al.*, "Mode Coupling Loss in Single-Mode Fibers with Depressed Inner Cladding", Journal of Lightwave Technology, Vol. LT-1, No. 3, September 1983, pp. 449-452.

Now, changing the refractive index n_3 of outer cladding **220** has the effect of shifting the phasematching wavelength λ_1 and can be used to eliminate coupling of radiation from core mode **224** to cladding mode **226** in accordance with the invention. Graphs **2110** and **2110′** in Figs. 20A and 20B illustrate the effective index n_{eff} experienced by core mode **224** when $n_3>n_2$ or $n_3<n_2$, respectively. Because a change in n_3 does not affect core mode **224** appreciably, graphs **2110** and **2110′** are almost identical. The effective indices of a number of cladding modes, including cladding mode **226** are indicated by lines **2112** and **2112′**, respectively.

In Fig. 21A the condition $n_3>n_2$ dictates that the effective indices of cladding modes can exceed n_2. In fact, the effective index of core mode **224** intersects with the effective index of cladding mode **226** at intersection point **2114** in the short wavelength range below cutoff wavelength λ_c. Furthermore, effective index of core mode **224** also intersects with the effective indices of two additional cladding modes in this case. Therefore, cladding mode losses due to coupling between core mode **224** and cladding mode **226** as well as coupling between core mode **224** and the two additional cladding modes exist. The coupling behavior is as indicated by graphs **2106′**, **2106″** and **2108′**, **2108″** in Fig. 19 (depending on the value of cladding loss α) and causes the undesired cladding mode loss.

On the other hand, when $n_2>n_3$ the effective indices of cladding modes cannot exceed n_2, as shown in Fig. 20B. Thus, the effective index of core mode **224** does not intersect with any cladding modes below cutoff wavelength λ_c. Therefore, there is no coupling between core mode **224** and cladding mode **226** or any other cladding mode below cutoff wavelength λ_c. In fact, the intersection point **2114'** between core mode **224** and cladding mode **226** occurs above cutoff wavelength λ_c in the long wavelength range in which ASE is being suppressed by the design of fiber amplifier **200**, as discussed above. The same is true for coupling from core mode **224** to the other cladding modes.

The phasematching principle is used in accordance with the invention by introducing a non-phase-matched length section L of fiber amplifier **200** in which $n_3<n_2$ to suppress cladding mode loss. Referring to Fig. 6, in this embodiment, fiber amplifier **68** is similarly designed as fiber amplifier **200**. Fiber amplifier **68** is used in a system **1200** to amplify a signal **78** at wavelength λ_1 propagating through a fiber **80**. System **1200** has a pump source **86** providing a pump radiation **88** at wavelength λ_p. Pump radiation **88** is coupled from source **86** into a fiber **82**.

A fiber coupler **84** receives fibers **80** and **84** and couples them into a single output fiber **90**. Output fiber **90** is connected to fiber amplifier **68**.

During operation, signal **78** and pump radiation **88** are combined in coupler **84** and launched together through output fiber **90**. Fiber **90** delivers signal **78** and radiation **88** to active core **70** of fiber amplifier **68**. In accordance with the above-described principles, signal **78** is amplified in core **70**. Meanwhile, pump radiation **88** is depleted in passing through core **70**, as indicated. In fact, at the end of non-phase matched section L there may be little pump radiation remaining in fiber amplifier **68**.

ASE radiation at a wavelength λ_2 is generated as a by-product of pumping active core **70.** Wavelength λ_2 is longer than cutoff wavelength λ_c of fiber amplifier **68** and is therefore lost into outer cladding **76.** At the same time, some of signal **78,** which travels in core mode, is also lost into outer cladding **76** because of cladding mode losses. However, since non phase-matched length section L has an index n_3 lower than n_2, the amount of loss of signal **78** to outer cladding **76** is minimized.

System **1200** using non-phase-matched length section L of fiber amplifier **68** is thus capable of suppressing mode loss at wavelengths shorter than the cutoff wavelength. In fact, fiber amplifier **68** can be effectively employed in various optical systems.

In another alternative embodiment, the use of a non-phase-matched length section and the use of an absorbing or scattering materials can be combined in one fiber amplifier. For example, the scattering or absorbing material may constitute a part of the outer cladding or the entire outer cladding in such alternative embodiments.

Yet another embodiment in accordance with the invention employs a non-phase-matched length section L which prevents phase matching between core and cladding modes by varying the cross-sectional profile of a fiber amplifier **2150** as shown in Figs. 21A and 21B. Fig. 21A shows the cross-section of fiber amplifier **2150** at a position $L=x_1$. Fiber amplifier **2150** has an active core **2152** surrounded by a cladding **2154** having a varying cladding index n_{clad}. A minimum value of n_{clad} is indicated by line **2156.** A graph of index profile **2158** showing the variation of n as a function of radius r is shown above fiber amplifier **2150**. A person skilled in the art will appreciate that, in general, n_{clad} can vary as a function of radius r and azimuthal angle θ, i.e., $n_{clad}=n_{clad}(r,\theta)$.

At position $L=x_2$ the cross section of fiber amplifier **2150** is different, as shown in Fig. 21B. In particular, index profile **2158'** remains the same as index profile **2158** in and near active core **2152** to ensure the same cutoff wavelength λ_c and loss curve for longer wavelengths are the same at positions x_1 and x_2. However, the portion of index profile **2158'** further away from core **2152** within cladding **2154** exhibits a different curvature and minimum value than index profile **2158**. Specifically, the location of the new minimum value of n_{clad} in index profile **2158'** is indicated by line **2156'**. Because of this variation of index profile from **2158** at x_1 to **2158'** at x_2, the wavelength for which cladding mode loss is phasematched at position x_1 is different from the wavelength for which cladding mode loss is phasematched at position x_2. Therefore, phase matching between core mode and cladding modes in fiber amplifier **2150** is prevented.

As mentioned heretofore, the fiber amplifier of the present invention can contain any suitable active medium in its active core. For example, the active core can be doped with Neodymium, Erbium, or Thulium ions. When using Erbium, the fiber amplifier is an EDFA and in one advantageous embodiment its cutoff wavelength λ_c is set near 1525 nm. Specifically, Erbium **18** acts as a lasing medium and exhibits high gains in a long wavelength band including the C- and L-bands. Erbium **18** also has positive gains in a short or S-band of wavelengths shorter than the wavelengths in the C- and L-bands. When pumped to a high relative inversion D, the high gains of Erbium **18** in the long wavelength band cause amplified spontaneous emissions (ASE) or lasing which reduces the population inversion of Erbium **18** and thus reduces the positive gains in the S-band. As discussed before, by selecting the core cross-section, the depressed cladding cross-section, and the refractive indices n_o, n_1, and n_2 to produce losses at least comparable to the high gains in the long wavelength band and losses substantially smaller than the positive gains in said S-band, the W-index profile of the inventive fiber nevertheless enables the fiber to effectively amplifying signals in the S-band.

In another example, Thulium is doped into fused-silica fibers. Although the Thulium gain is typically thought to be at 1.9 microns, and indeed that is the peak of the gain, the wavelength range over which gain is possible stretches from 1.5 microns to 2.1 microns. The typical Thulium pump wavelength is 0.78 microns. However, it is also possible to pump Thulium at 1.48 microns or about 1.5 microns, though very high intensities would be needed, possibly as high as 100 mW.

Graphs **A** and **B** in Fig. 39 show that the Thulium has fluorescent emission from 1.6 to 2 μm. The shape of the fluorescence spectrum is very similar to that of the gain spectrum, except that the gain will be at a slightly longer wavelength than the fluorescence. If Thulium acts as an ideal ion, as do Erbium and Ytterbium, then gain should be possible to stretch from 1.5 μm to 2.1 μm. The peak of the gain will be between 1.8 and 1.9 microns. The gain cross-section and the upper-laser-level lifetime of the Thulium ion are similar to those of the Erbium ion. Thus, the threshold for gain is similar - several milliwatts of pump power are required.

The Thulium 3+ ion could be used on the short-wavelength end of its gain region in exactly the same way as the Erbium ion. By pumping with an intense pump (30 mW or so) it is possible to reach inversion even at short wavelengths. However, before high gain is reached at a short wavelength such as 1.6 microns, there will be overwhelming superfluorescence near 1.9 microns.

A useful amplifier can be made at the shorter wavelength if the fiber is designed with a fundamental mode cut-off between 1.9 microns and the shorter wavelength of desired operation, and if the cut-off is such that the increase in loss at longer wavelengths exceeds the increase in gain due to the higher cross-section. In an embodiment, the long wavelength band is about 1.7 to 2.1 microns, the short wavelength band is the L-band, which is roughly 1.6 to 1.8 microns, the cut-off wavelength is about 1.7 to 1.9 microns, and the pump wavelength is about 1.48 to 1.5 microns. The cut-off wavelength is selected such that the increase in loss at longer wavelengths exceeds the increase in gain due to the higher cross-section. This technique makes it possible to build useful amplifiers in the wavelength range between about 1.6 to 1.8 microns. Since telecommunication fiber is highly transmissive in this range, it is anticipated that amplifiers that work in this wavelength range will be highly desirable.

Fig. 22 illustrates a source **300** of light in the S-band employing a fiber **302** doped with Erbium **306** and constructed to form an EDFA in accordance with the above principles. Specifically, fiber **302** has a core **304** doped with Erbium **306**, a depressed cladding **308** surrounding core **304** and a secondary cladding **310** surrounding depressed cladding **308**.

Source **300** has a pump source **312** for providing a pump light **314.** Pump source **312** is preferably a diode laser emitting pump light **314** at a wavelength of about 980 nm. An optic **316** in the form of a lens is provided for coupling pump light **314** into a fiber **318.** A coupler **320** is provided for coupling pump light **314** from fiber **318** into a fiber **324.** Fiber **324** is joined to one end of fiber **302** in accordance with any suitable fiber splicing technique known to those skilled in the art such that fiber **324** delivers pump light **314** into core **304** of fiber **302.**

Pump source **312** is controlled by a pump control **322** such that source **312** delivers pump light **314** for pumping Erbium **306** in core **304** to a high relative inversion D. The relative inversion D is sufficiently high when Erbium **306** exhibits positive gains in the S-band and high gains in the long wavelength band, i.e., the L- and C-bands. The cross-sections and refractive indices, n_o, n_1, n_2 of core **304,** depressed cladding **308** and secondary cladding **310** are selected in accordance with the above rules. In particular, the cross-sections and refractive indices n_o, n_1, n_2 are selected to produce losses at least comparable to the high gains in the L- and C-bands and losses substantially smaller than the positive gains in the S-band.

Fiber **324** passes through coupler **320** and is terminated by a wavelength-selecting device **326.** In the present embodiment device **326** is a wavelength-selecting feedback mechanism in the form of a fiber Bragg grating. Fiber Bragg grating **326** is a wavelength-selecting feedback mechanism because the portion of light that it is tuned to reflect propagates through fiber **324** back into fiber **302.** Of course, other mechanisms can also be used. For example, another advantageous wavelength-selecting feedback mechanism is a tunable free-space diffraction grating configured to retro-reflect light at the desired output wavelength.

At its other end fiber **302** is joined with a fiber **328** that is terminated by an output coupler **330**. Once again, any suitable fiber joining technique can be employed to join the end of fiber **302** to fiber **328**. The junction is such that light propagating through core **304** of fiber **302** is freely coupled between fiber **302** and fiber **328**. Output coupler **330** is any suitable optical coupling device for passing an output light **332**. For example output coupler **330** can be a cleaved end of fiber **328**, i.e., a cleaved output facet, a wavelength coupler, a free-space reflector, a fiber Bragg grating, a 2x2 fused fiber coupler used in conjunction with a broadband reflector. In fact, any output coupling device used to couple output light from a fiber laser can be used as output coupler **330** including a diffraction grating. In fact, as will be appreciated by a person skilled in the art, a diffraction grating can be used to serve the function of wavelength selecting device **326** and output coupler **330**.

During operation pump laser control **322** is turned on to provide pump light **314** to fiber **302** such that Erbium **306** is pumped to a high relative inversion D. As a result, Erbium **306** exhibits positive gains in the S-band and high gains in the L- and C-bands. The selection of cross-sections and refractive indices n_o, n_1, n_2 of core **304**, depressed cladding **308** and secondary cladding **310** in accordance with the invention cause losses at least comparable to the high gains in the L- and C-bands and losses substantially smaller than the positive gains in S-band **342**. Therefore, fiber **302** exhibits a net optical gain spectrum that extends several tens of nanometers below fundamental mode cutoff wavelength λ_c within S-band **342**.

Fig. 23 shows a shortest wavelength λ_{short} and a longest wavelength λ_{long} for which the gain is positive define a net gain bandwidth **390**. Shortest and longest wavelengths λ_{short}, λ_{long} are determined by design parameters of fiber **302** including a roll-off loss curve below cutoff wavelength λ_c, doping concentration, and distribution of Erbium **306** in core **304**, and average degree of inversion D over the length of fiber **302**. Changes in the length of fiber **302** do not impact shortest and longest wavelengths λ_{short}, λ_{long} for which the gain is positive as long as inversion D remains constant. Changes in the length of fiber **302**, however, impact the amount of gain within net gain bandwidth **390** contained between shortest and longest wavelengths λ_{short}, λ_{long}. On the other hand, changes in the power of pump light **314** and its direction as well as single-end or dual-end pumping directly affect the average degree of inversion D in fiber **302**. The present embodiment employs single-end pumping in which pump light **314** and output light **332** are co-propagating (propagate in the same direction). Higher inversion D produces higher gain (or lower loss) at all wavelengths within S-band **342** and can also expand net gain bandwidth **390** between shortest and longest wavelengths λ_{short}, λ_{long}.

Even when fiber **302** does not receive a signal light for amplification (e.g., signal light **78** as illustrated in Fig. 6) it still creates an optical output. Unavoidable fluorescence also referred to as spontaneous emission (SE) occurs due to the natural radiative decay of excited (pumped) atoms of Erbium **306** back down to ground state. The spontaneous emission process happens in exact proportion to the spectrum of the "emission cross section" (often called the gain cross section, due to their correspondence). In fact, even if population inversion has not been achieved, spontaneous emission still occurs. Some of this spontaneous emission generates light within S-band **342**, and some of this light overlaps with a mode guided by fiber **302**. More specifically, some of the light produced by spontaneous emission is trapped in core **304** of fiber **302** and travels along its core **304** in a guided mode. Of that trapped light the portion that overlaps with net gain bandwidth **390** of fiber **302** is amplified. Light outside net gain bandwidth **390** is generally not amplified and is lost by direct attenuation, absorption by non-inverted atoms of Erbium **306** and loss to secondary cladding **310** among other. In this case, ASE is guided in core **304** and amplified by fiber **302**.

As will be appreciated by those skilled in the art, the spectral shape of the ASE is determined both by the spectral shape of the spontaneous emission (which is related to the emission cross section) and also by the spectral shape of the net gain bandwidth **390**. Net gain bandwidth **390** is related to the emission cross section, absorption cross section, degree of inversion D and the spectral shape of the losses dictated by roll-off loss curve produced by the selection of cross sections and refractive indices of fiber **302**. However, the spectral shape of ASE is not merely the product of the spontaneous emission spectrum and the spectrum associated with net gain bandwidth **390**, as would be expected if all of the spontaneous emission happened at one end of fiber **302** and all of the amplification occurred at a different location in fiber **302**. Rather, the ASE output from fiber **302** is the superposition of the amplified bits of spontaneous emission originating at each and all locations within fiber **302**.

In general, wavelengths at which there are high gains and high losses exhibits higher ASE power than wavelengths with low gains and low losses, even if the net gain is the same. Typically, due to the shape of the emission cross section of Erbium **306**, longer wavelengths within net gain bandwidth **390** exhibit higher gains than shorter wavelengths. Also, typically, longer wavelengths exhibit higher losses than shorter wavelengths. The higher losses are due to the shape of the absorption cross section of Erbium **306** and the shape of the roll-off loss curve. Hence, the ASE spectrum of S-band amplifier constituted by fiber **302** is often biased towards these longer wavelengths, even though the longest of these wavelengths may experience net loss. Typically, the shorter wavelengths of the ASE emission spectrum exhibit small positive net gains, through not much ASE power.

As a result of the above phenomena the following rules should be observed when constructing source **300**. First, one should select a peak wavelength λ_{peak} within net gain bandwidth **390**. Then, the cross sections and refractive indices of core **304**, depressed cladding **308** and secondary cladding **310** should be selected to set cutoff wavelength λ_c about 10-20 nm above λ_{peak}. The exact distance between λ_{peak} and λ_c should be adjusted depending on the steepness of roll-off loss curve **38** (see Fig. 4). In particular, when roll-off loss curve **38** is steep then λ_c should be set only about 10 nm above λ_{peak}. On the other hand, for a less steep roll-off loss curve a cutoff wavelength λ'_c should be set up to 20 nm above λ_{peak}. The general shape of the ASE emission spectrum has the shape of the net gain spectrum within net gain bandwidth **390** as indicated by graph **392** for steep roll-off loss curve and by graph **392'** for less steep roll-off loss curve.

Next, one should determine the desired power level and bandwidth of source **300**. To obtain output light **332** at a high power level fiber **302** is lengthened. The doping concentration of Erbium **306** in core **304** can be kept the same or even increased to further aid in increasing the power level of light **332**. Then, the power level of pump light **314** is increased, e.g., to obtain 100-200 dB absorption of pump light **314** in fiber **302**. For example, pump light **314** is delivered at a power level such that fiber **302** absorbs up to 90% of pump light **314**. On the other hand, to obtain output light **332** spanning a wide bandwidth, fiber **302** is kept short and the power level of pump light **314** is decreased.

Thus, there exists a tradeoff between power and bandwidth. This is because for the high gains and wide amplification bandwidths that can be achieved in doped EDFAs the ASE process is quite efficient. The typical way of further increasing the power of an EDFA is to pump harder and/or lengthen the EDFA. This approach works well up to a point. However, the fiber length and pumping cannot be increased as much as desired due to the high efficiency of the ASE process. Once a significant ASE power builds up in an EDFA, e.g., up to net gains of 40 dB, the ASE process begins to rob the population of Erbium atoms in the excited state, thereby reducing the degree of inversion D. Reduced inversion D causes a reduction of spontaneous emission and a significantly reduced amount of net gain. The S-band EDFA is particularly sensitive to reductions in inversion D because of the unfavorable radio of emission cross section to absorption cross section within the S-band. This interplay between ASE and gain limits the available power and/or bandwidth of ASE within the S-band when a single EDFA section is used. Therefore, if sufficient power over the desired bandwidth cannot be achieved with fiber **302**, then several fibers analogous to fiber **302** can be used in combination. Further details of such combinations are described below.

As fiber **302** is being pumped by pump light **314**, source **300** generates ASE emission spectrum **392** centered about peak wavelength λ_{peak}. Lasing operation of source **300** is obtained with the aid of fiber Bragg grating **326**. Specifically, fiber Bragg grating **326** is set to reflect an output wavelength λ_{output} within ASE emission spectrum **392**. At the same time, output coupler **330** is set to pass a fraction of light **332** at wavelength λ_{output}. After many round trips between fiber Bragg grating **326** and output coupler **330**, light at λ_{output} dominates over ASE emission spectrum **392**. Therefore, source **300** emits output light **332** having a narrowband spectrum **334** centered at wavelength λ_{output} through output coupler **330**. Pump source control **322** can operate in a continuous mode or in a pulsed mode. Therefore, output light **332** can be delivered in pulses or continuously, as desired.

Fig. 24 illustrates an alternative embodiment of a source **340** in which parts corresponding to those of source **300** are referenced by the same reference numerals. Source **340** differs from source **300** in that it has a wavelength selecting mechanism **342** and a control **344** for adjusting the wavelength reflected back to fiber **302** by mechanism **342**. Wavelength selecting mechanism **342** is a wavelength filter such as a tilted etalon, a strain-tuned fiber Bragg grating, a temperature-tuned fiber Bragg grating, an interferometer, an array of waveguide gratings, a diffraction gratings or a tunable coupled cavity reflector. Correspondingly, control **344** is a mechanism for controlling stain, temperature, inclination angle or other required tuning parameter of filter **342**, as will be appreciated by a person skilled in the art.

By controlling the wavelength band reflected by filter **342** an output wavelength λ_{output} of light **332** is selected as in source **300**. Of course, output coupler **330** is adjusted to pass light **332** at the selected output wavelength λ_{output}. One can also select several output wavelengths within ASE emission spectrum **392** (see Fig. 23).

Alternatively, or in combination with output wavelength selection performed with the aid of filer **342**, pump source control **322** of source **340** can also be used to adjust the output wavelength of light **332** by tuning the level of relative inversion D. This is achieved by tuning the power delivered by control **322** to pump source **312**. Changing the power level applied to pump source **312** adjusts the intensity of pump light **314**, hence tuning the level of relative inversion D, as will be appreciated by a person skilled in the art.

Fig. 25 illustrates a preferred embodiment of a source **360** according to the invention using a single EDFA **364**. Source **360** does not require the use of reflectors by virtue of having a fiber ring cavity **362** with an output coupler **366**. In this embodiment, a wavelength filter **368** installed in ring cavity **362** serves as a wavelength selecting mechanism. Filter **368** can be an adjustable filter, preferably a diffraction grating used in conjunction with an optical circulator or a temperature controlled fiber Bragg grating with a suitable control mechanism (not shown), an acousto-optic transmission filter (AOTF) or even a tunable etalon. Fiber ring cavity **362** also has an isolator **370** for controlling back-reflections and preventing output light **372** containing the light fraction at

λ_{output} or the ASE from propagating in both directions around ring **362**. During operation EDFA **364** is pumped by a pump source (not shown) and operated in accordance with the principles described above.

Fig. 26 illustrates a source **361** also using a fiber ring cavity **363**. In order to obtain a broader ASE emission spectrum, source **361** employs two EDFAs **365, 367** connected in parallel between two couplers **371, 373**. A third coupler **371** is employed for deriving output light **377** from ring cavity **363**. The pump sources providing pump light to EDFAs **365, 367** are not shown in this embodiment for reasons of clarity.

EDFAs **365, 367** have different ASE emission spectra. These ASE emission spectra can be controlled by any of the above-discussed mechanisms, including different fiber parameters (cross sections, refractive indices and roll-off loss curves), lengths and inversion levels set by the intensity of pump light (not shown). Preferably, the ASE emission spectra of EDFAs **365, 367** are chosen to have their peak wavelengths at different locations within the S-band to thus span a wider total ASE emission spectrum. Thus, source **361** is able to provide a broader ASE emission spectrum and offers a wider range of wavelengths within which the output wavelength λ_{output} is selected by filter **369**. Furthermore, source **361** also has an isolator **375** for controlling back-reflections and preventing output light **377** containing the light fraction at λ_{output} or the ASE from propagating in both directions around ring cavity **361**.

During operation wavelength filter **369** sets output wavelength λ_{output} of light **377** within the total ASE emission spectrum provided by EDFAs **365, 367**. Light **377** is outcoupled from ring cavity **363** through output coupler **371**, as shown. It should be noted that more than two EDFAs can be used to cover a still broader ASE emission spectrum. In fact, filter **369** can be left out completely in some embodiments to outcouple light **377** covering the wide bandwidth afforded by the parallel-configured EDFAs thus yielding a broadband source.

Source **361** can be easily adapted to cover more than just the S-band. For example, another EDFA covering the C- or L-band of wavelengths, or in fact several additional EDFAs, can be connected in parallel with EDFAs **365** and **367** and their outputs combined.

Fig. 27 illustrates yet another embodiment of a source **380** that uses a single EDFA **382**. Source **380** has a pump source **384** for providing pump light **386**. A lens **388** focuses pump light **386** into a fiber **390**, which is coupled to EDFA **382** by a coupler **392**.

EDFA **382** is coiled at a constant coiling diameter CD. To provide for mechanical stability, EDFA **382** can be coiled about a spool of diameter CD (not shown). In fact, the strain introduced into EDFA **382** by coiling diameter CD serves as the wavelength-selecting mechanism in this embodiment. That is because coiling diameter CD produces a desired ASE emission spectrum in EDFA **382**. Specifically, selecting a larger coiling diameter CD, e.g., CD′ as indicated, shifts the maximum of the ASE emission spectrum of EDFA **382** to longer wavelengths within the S-band.

EDFA **382** is terminated by an angle cleaved facet **394** or other non-reflective termination that prevents back reflection for better stability of source **380**. Thus, angle cleaved facet **394** ensures that a sufficient amount of stable and low-noise output light **402** is emitted by EDFA **382** to an output coupler **396**. An isolator **398** is interposed between EDFA **382** and output coupler **396** to prevent back-coupling of light **402** into EDFA **382**.

In this embodiment output coupler **396** has an additional tap **400** for deriving a small amount of output light **402**, e.g. about 1%, for output monitoring. A photodetector **404**, in this case a photodiode, is provided for measuring tapped output light **402**.

Source **380** can be used as a fixed source or as a tunable source. In particular, source **380** can be rendered tunable by providing a mechanism for altering coiling diameter CD. Alternatively, source **380** can be rendered broadband by widening the ASE emission spectrum of EDFA **382**, e.g., by selecting a less steep roll-off loss curve, as discussed above.

Source **380** employs a counter-propagating pumping geometry where pump light **386** is injected from a direction opposite to the direction in which output light **402** is derived from EDFA **382**. This approach is preferred to co-pumping arrangements used in the above-described embodiments where the pump light is delivered along the same direction as the direction along which output light is derived.

A preferred embodiment of a source **410** is shown in Fig. 28. Source **410** uses two EDFA sections (which may or may not belong to the same piece of fiber) specifically a first section **412** and a second section **414**. These two sections have different ASE emission spectra. In this case the ASE emission spectra are set by first and second coiling diameters CD1 and CD2 of sections **412, 414** respectively. Specifically, first section **412** has a smaller coiling diameter and second section **414** has a larger coiling diameter, CD1<CD2. Thus, the maximum of ASE emission spectrum of first section **412** is at a shorter peak wavelength λ_{peak} than the maximum of ASE emission spectrum of second section **414.**

As in the previous embodiment, an angle cleaved facet **416** prevents back reflection of output light **428.** EDFA sections **412, 414** are pumped by pump light **418** delivered from a pump source **420** in a counter-propagating pumping arrangement. In particular, pump light **418** is focused by a lens **422** into a fiber **424** and a coupler **426** couples pump light **418** from fiber **424** into EDFA sections **412, 414.**

An isolator **430** ensures that output light **428** is not coupled back into EDFA sections **412, 414.** An output coupler **432** is provided for outcoupling output light **428.** Output coupler **432** has a tap **434** for tapping a small portion of output light **428** and a photodetector **436** for monitoring the tapped portion of output light **428.**

It is important to note that in source **410** first section **412** is positioned before second section **414** such that first section **412** seeds second section **414.** In other words, the ASE from first section **412** propagates into second section **414** and output light **428** is derived from second section **414.** The reasons for this arrangement is that second section **414** offers positive net gain for light at wavelengths generated by first section **412.** First section **412,** however, does not offer positive net gain and hence does not amplify light at wavelengths generated by second section **414.** In other words, first section **412**, which emits light centered around a shorter peak wavelength λ_{peak} can be used to seed second section **414** but not vice versa. Still differently put, the two-coil design of source **410** does not cause significant depletion of inversion D in second section **414**, while reversing the order of sections **412** and **414** would and would hence degrade the operation of source **410**.

Fig. 29 illustrates the ASE emission spectrum of first section **412** at first coiling diameter CD1=2.2 inches and of second section **414** at second coiling diameter CD2=2.9 inches. Fig. 29 also shows the total ASE emission spectrum obtained when section **412** seeds second section **414**.

Based on the above principle, a number of EDFAs of different coiling diameters can be used in series from smallest diameter (shortest peak wavelength λ_{peak}) to largest diameter (longest peak wavelength λ_{peak}) to construct a still broader bandwidth source in accordance with the invention. Fig. 30 illustrates ASE emission spectra of five EDFAs having increasing coiling diameters ranging from 2.25 inches to 2.90 inches. Using these EDFAs in series makes it possible to construct a source spanning a wavelength range covering most of the S-band, i.e., from about 1460 nm to about 1525 nm.

Yet another method for broadening the ASE emission spectrum of an EDFA is by providing a continuously variable coiling diameter CD along the length of the EDFA. The coiling diameter should be increasing for seeding reasons, as explained above. A continuously variable coiling diameter can be produced, e.g., by winding the EDFA around a cone.

Fig. 32 illustrates yet another embodiment of a source **440** employing an EDFA having a first section **442** and a second section **444**. First section **442** has a smaller first coiling diameter and is used to seed second section **444** having a larger second coiling diameter. Source **440** has two separate pump sources **446, 448** with associated lenses **450, 452,** fibers **454, 456** and couplers **458, 460** for delivering pump light **462** to first section **442** and pump light **464** to second section **444.**

Source **440** has an angle cleaved facet **466** terminating first section **442.** Source **440** employs an isolator **468** between first section **442** and second section **444** for stabilization. A tunable filter **470** installed after isolator **468** and before second section **444** is used to tune output wavelength λ_{output} of output light **472.** Conveniently, coupler **460** is used as output coupler for light **472** in this embodiment.

Source **440** enables the operator to quickly and easily adjust the levels of pump power delivered by pump light **462** and **464** to sections **442** and **444** for tuning of output light **472.** In fact, Fig. 31 illustrates how the use different levels of pump power in first and second sections **442, 444** tunes the total ASE emission spectrum for coiling diameters of first and second sections **442, 444** equal to 2.25 and 2.5 inches respectively.

Fig. 33 illustrates a source **480** employing a similar arrangement as source **440.** Corresponding parts of source **480** are referenced by the same reference numerals. Source **480** uses a single pump source **482** for delivering pump light **484** to both sections **442, 444.** This is done with the aid of lens **486,** coupler **488** and fibers **490, 492** as shown. The coupling ratio of coupler **488** between fibers **490** and **492** can be adjusted to control the levels of pump power delivered by pump light **484** to section **442** and section **444**. The methods to adjust this coupling ratio are well-known to those skilled in the art.

Of course, an EDFA in accordance with the invention can also be seeded by other means than a preceding EDFA section. Fig. 34 illustrates in a simplified diagram a source **500** in which an EDFA **502** is seeded by a master oscillator **504**. Master oscillator **504** can be any suitable source such as a distributed feedback laser, Fabry-Perot laser, external cavity diode laser, distributed Bragg reflector laser, vertical cavity surface emitting laser, semiconductor laser, a fiber laser or a broadband source. Input light **506** from master oscillator **504** is coupled into EDFA **502** by a lens **508**. Output light **510** can be derived directly from EDFA **502** or with the aid of any suitable output coupling mechanism.

Alternatively, the sections of EDFA fiber in any of the preceding embodiments using coiling diameter to control the ASE emission spectrum and the peak wavelength can take advantage of appropriate selection of core cross-section, depressed cladding cross-section, and refractive indices n_o, n_1, and n_2. Specifically, in the first section a first cutoff wavelength λ_{c1} is produced by appropriate selection of these parameters. In the second section a second cutoff wavelength λ_{c2} longer than said first cutoff wavelength λ_{c1} is produced. Then, the first section is positioned before the second section for seeding the second section in the same manner as discussed above. Preferably, an isolator is positioned between these two sections. Of course, an additional adjustment of the ASE emission spectrum of the two sections can be performed by coiling the first and second sections as necessary.

Fig. 35 illustrates the use of a source **520** according to the invention to test a device under test **522** (DUT) for performance characteristics in the S-band. An optical spectrum analyzer **524** is provided to measure the response of DUT **522**. Source **520** generates test light **526** by using any of the above described configurations. Light **526** can span a wide band or be tuned to a particular output wavelength λ_{output}, as required for testing DUT **522**.

The method of producing short-pass fibers in accordance with the invention will be discussed with reference to Fig. 36, which shows a preform **600** for a depressed cladding fiber designed for pulling a short-pass fiber **620**. Preform **600** has a core **612** surrounded by a depressed cladding **614**. A secondary cladding **616** surrounds depressed cladding **614**. Preform **600** is made of primary glass constituent SiO_2 and is manufactured by hydrolysis, oxidation, sol-gel or any other suitable method.

Core **612** has a core cross-section that is circular and is described by a core radius r_c. Depressed cladding **614** and secondary cladding **616** have corresponding circular cross-sections described by radii r_{dc} and r_{sc}, respectively. Core **612** has a refractive index n_o, depressed cladding **614** has a refractive index n_1 and secondary cladding **616** has a refractive index n_2. Refractive index n_o of core **612** is the highest, while refractive index n_1 of depressed cladding **614** is the lowest. In the present embodiment, refractive index n_o is attained by doping core **612** with index-raising dopant such as germanium or aluminum. Refractive index n_1 is attained by doping depressed cladding **614** with an index-lowering dopant such as boron or fluorine. Secondary cladding **616** remains undoped and its refractive index n_2 is that of the primary glass constituent SiO_2. The incorporation of index-raising dopant ions in core **612** and index-lowering dopant ions in depressed cladding **614** is performed in accordance with the hydrolysis or oxidation processes.

Fig. 37A is a graph illustrating a typical refractive index profile **622** obtained in practice in preform **600** as a function of radius (r), i.e., the transverse portion of index profile **622**. The incorporation of index-raising dopant ions in core **612** and index-lowering dopant ions in depressed cladding **614** in either the hydrolysis or oxidation processes is controlled by the equilibria established during dopant reaction, deposition, and sintering. As a result, a depression **624** in refractive index is present in core **612** of preform **600**. The equilibria further cause a sawtooth pattern **626** in refractive index to manifest in depressed cladding **614**. Thus, refractive index n_o of core **612** is in fact an average refractive index. Likewise, refractive index n_1 of depressed cladding **614** is also an average refractive index. Meanwhile, refractive index n_2 of secondary cladding **616** is also an average refractive index. The actual value of the refractive index in secondary cladding **616** exhibits comparatively low variability as a function of radius because refractive index n_2 is not attained by doping.

In addition to exhibiting radial variation, actual refractive index profile **622** also varies as a function of position along an axis **627** of preform **600**. In other words, profile **622** has a longitudinal portion varying along the length of preform **600**. Preform **600** has a total length L and the variation of the refractive index at preselected radii as a function of length is illustrated in the graphs of Fig. 37B. Once again, refractive indices n_o and n_1 are average refractive indices while the actual refractive index values exhibit a large variation. Meanwhile, refractive index n_2 is also an average refractive index while the actual refractive index value remains relatively constant. Depending on the specifics of the manufacturing processes, the actual refractive index values in core **612** and depressed cladding **614** exhibit tolerance ranges TR_1 and TR_2 that may approach up to 20% along the length of axis **627.**

Fig. 36 also shows how short-pass fiber **620** is obtained by drawing or pulling preform **600** from an initial cross sectional area A_o to a final total cross sectional area A_f. Initial and final cross sectional areas are equal to:

$$A_o = \pi r_{sc}^2, \text{ and}$$
$$A_f = \pi r_2^2,$$

where r_2 is the radius of secondary cladding in pulled short-pass fiber **620.** A drawing ratio DR is defined as the ratio of the radius of the fiber to the radius of the preform:

$$DR = \frac{r_2}{r_{sc}}$$

Since the refractive indices are nearly preserved during the pulling process, the average index n_o of core **612** is significantly higher than the average index n_1 of depressed cladding **614** and average index n_2 of secondary cladding **16** in pulled short-pass fiber **620.** The drawing ratio DR by which preform **600** is to be pulled to obtain radii r_o, r_1, r_2

corresponding to core **612**, depressed cladding **614** and secondary cladding **616** in pulled short-pass fiber **620** is made to achieve certain guiding properties in short-pass fiber **620**. Specifically, the indices and radii are selected to produce a fundamental mode cutoff wavelength λ_c such that light in the fundamental mode at wavelengths smaller than λ_c is retained in core **612** while light in fundamental mode at wavelength λ_c or longer wavelengths is lost to secondary cladding **616** over a short distance. This objective is accomplished by ensuring that pulled short-pass fiber **620** exhibits the appropriate average refractive indices n_o, n_1, n_2 and cross-sections or radii r_o, r_1, r_2. In other words, this goal is accomplished by appropriately engineering refractive index profile **622** and cross-sections of core **612**, depressed cladding **614** and secondary cladding **616**, or, still differently put, by obtaining the appropriate W-profile, such as the index profile **20** shown in Fig. 1, in short-pass fiber **620**.

In any practical short-pass fiber **620** the depressed cladding cross-section has to be larger than the core cross-section. This is ensured by selecting the core cross-section A_c smaller than depressed cladding cross-section A_{dc} in preform **600**. Specifically, in preform **600** core cross-section is equal to:

$$A_c = \pi r_c^2, \qquad (16)$$

while the depressed cladding cross section is equal to:

$$A_{dc} = \pi (r_{dc}^2 - r_c^2). \qquad (17)$$

The aerial ratio established between core and depressed cladding cross-sections (A_c/A_{dc}) is preserved during the pulling of preform **600** into short-pass fiber **620**. Likewise, the values of average refractive indices n_o, n_1, n_2 are nearly preserved during the pulling.

The values of r_o, r_1, n_o, n_1 and n_2 in short-pass fiber **620** not only define fundamental mode cutoff wavelength λ_c but also define a roll-off loss curve with respect to wavelength. Fig. 38 illustrates an exemplary family of loss curves **640** for the same fundamental mode cutoff wavelength λ_c. It has been found that only the cutoff wavelength λ_c gets displaced during the pulling of short-pass fiber **620** from preform **600**. In other words, the overall shapes of roll-off loss curves **640** are basically preserved.

Unfortunately, the actual fundamental cutoff wavelength will differ from point to point along axis **627** due to the variation in index profile **622** along axis **627**. In fact, given that tolerances TR_1 and TR_2 for refractive indices n_o and n_1 vary up to 20% (see Fig. 37B), the actual cutoff wavelength can fluctuate by up to about 20%. Therefore, it is clearly not feasible to simply pull preform **600** at the computed drawing ratio DR to produce short-pass fiber **620** with the calculated fundamental mode cutoff wavelength λ_c.

Thus, in accordance with the method of invention, a minimum fundamental mode cutoff wavelength λ_m is set before pulling preform **600**. Specifically, minimum cutoff wavelength λ_m is set to be the smallest possible value that cutoff wavelength λ_c can assume at any point along axis **627** in pulled short-pass fiber **620**.

Furthermore, core cross-section A_c and depressed cladding cross-section A_{dc} are measured in preform **600** before pulling. In the present embodiment, where core **612** and depressed cladding **614** are circular this is done by measuring radii r_c, r_{dc} and using the equations given above. Preferably, the values of radii r_c, r_{dc} are measured at a number of locations along axis **627** to obtain average values.

The longitudinal portion of refractive index profile **622** in core **612** and depressed cladding **614** is measured along axis **627** of preform **600** as well. This is conveniently performed by taking measurements of actual values of refractive indices n_o, n_1 at regular intervals along axis **627** and at a number of radii to thus obtain the average values of refractive indices n_o, n_1. Such measurements can be performed by deflection tomography, which is well known in the art of optical fiber preform characterization. It is also convenient to plot the measurements of refractive indices n_o, n_1 in the form of a graph of average values at each point along axis **627**, similar to the graph shown in Fig. 37A.

In accordance with the invention drawing ratio DR is derived from measured core cross-section A_c, depressed cladding cross-section A_{dc} and the variation in indices n_o, n_1 determined in preform **600**. In particular, drawing ratio DR is set to achieve a final value of core cross-section A'_c. In this embodiment final value of core cross-section A'_c is defined by the final core radius r_o to be obtained in short-pass fiber **620**. This is done such that, given a final depressed cladding cross section A'_{dc} and indices n_o, n_1 final core radius r_o defines fundamental mode cutoff wavelength λ_c such that $\lambda_c \geq \lambda_m$ at all points along axis **627**. Preferably, λ_m is set at least 5 nm below a lowest value of fundamental cutoff wavelength λ_c along axis **627**. This is done as a precaution so that subsequent fine adjustment of fundamental mode cutoff wavelength λ_c in pulled short-pass fiber **620** is still possible by standard techniques, such as stressing or bending of the fiber.

Referring back to Fig. 36, in the next step preform **600** is pulled by drawing ratio DR determined in accordance with the above-defined rules. It is important to get as close as possible to the desired core radius r_o during this pull. For example, when core radius r_o is within 0.5% of the desired core radius, the error in cutoff wavelength λ_c is within 0.5%. This corresponds to a 5 nm error in cutoff wavelength λ_c when operating at a wavelength of 1.0 micron and an 8 nm error when operating at a wavelength of 1525 nm. This type of error is barely acceptable for short-pass fibers used for S-band amplification with Er-doped fiber, and is more than adequate for short-pass fibers used for amplification at 980 nm with Nd-doped fiber.

In accordance with a preferred embodiment a short pilot section or test section **634** of preform **600** is pulled first by drawing ratio DR. The pulling of test section **34**, sometimes also referred to as pilot draw, aids in eliminating systematical errors. That is because the process of pulling can modify index profile **622**. For example, the pulling process tends to produce a smoothing of index profile **622** due to melting of the glass during the pulling process. Melting tends to shift actual fundamental mode cutoff wavelength λ_c to shorter or longer wavelengths depending on the details of the design of refractive index profile **622** of perform **600** and any index raising or lowering materials it uses. For example, index-lowering dopants consisting of small atoms such as Fluorine diffuse easily in softened silica glass. Thus, an index-lowering dopant such as Fluorine diffuses into core **612** and shifts cutoff wavelength λ_c to a shorter wavelength. This is problematic when depressed cladding **614** is deep and wide, so that significant diffusion into core **612** occurs without appreciably affecting the average refractive index of depressed cladding **614**. Thus, the pilot draw is useful because the smoothing of profile **622** cannot be calculated or modeled with sufficient accuracy to determine its effect on fundamental mode cutoff wavelength λ_c.

After pulling of test section **634** fundamental mode cutoff wavelength λ_c is determined in pulled test section **634**. This is preferably done at several points along axis **627**. It is important to choose test section **634** long enough to be representative of preform **600** and hence of short-pass fiber **620** that will be pulled from preform **600**. For this reason test section **634** should be chosen to be between a few percent and up to 20 percent of length L. The cutoff wavelength may be determined experimentally as the wavelength at which light is lost from the core at a significantly high rate, for example, at 10 dB/m or 40 dB/m.

Based on the deviation of fundamental mode cutoff wavelength λ_c measured in pulled test section **634** drawing ratio DR is adjusted to an adjusted drawing ratio DR′ as follows:

$$DR' = DR \cdot \frac{desired\ \lambda_c}{measured\ \lambda_c}$$

Then the remainder of preform **600** is pulled by adjusted drawing ratio DR′ to produce short-pass fiber **620**.

This preferred embodiment of the method is especially useful in situations when preform **600** exhibits a sufficiently high uniformity such as about 0.5% for radii or indices. At this level of uniformity compensation for dopant diffusion and other systematic effects is very effective. However, even in cases where such uniformity is not present, it is still convenient to pull test section **634** and measure the deviation of fundamental mode cutoff wavelength λ_c in test section **634** to determine adjusted drawing ratio DR′ for pulling the remainder of preform **600**.

In an alternative embodiment, drawing ratio DR is varied as the preform is pulled to compensate for the variations in refractive index graphed in Fig. 37B. This variable drawing ratio DR(z) is used to obtain an approximately constant cutoff wavelength λ_c along the length of the fiber. As above, the variable drawing ratio DR(z) may be multiplied by a factor λ_c*(desired)*/λ_c*(measured)* once the cutoff wavelength of the test section is measured, to compensate for systematic errors due to the pulling process.

In some embodiments of the method secondary cladding cross-section is adjusted before the pulling step. In the present embodiment this is done by increasing or decreasing secondary cladding radius r_{sc}. For example, radius r_{sc} of secondary cladding **616** is augmented by a rod-in-tube (also sometimes called "sleeving") technique or outside vapor deposition (OVD). Alternatively, radius r_{sc} of secondary cladding **616** is reduced by a technique such as etching. For more information on these techniques the reader is referred to *Erbium-Doped Fiber Amplifiers Fundamentals and Technology* by P. C. Becker, N. A. Olsson, and J. R. Simpson, chapter 2 (Optical Fiber Fabrication), published by Academic Press, pp. 13-42. The necessity to augment or reduce secondary cladding cross-section before pulling it arises when the pulled fiber is supposed to have a certain, e.g., standard, outside diameter

(OD), such as 125 +/-1 microns or 80 +/-1 microns. It is important to maintain standard fiber OD when low loss splicing to standard single mode fiber is required. The remainder of the method is performed in accordance with the above-discussed principles for designing short-pass fiber **620**.

The method of invention can be used for pulling short-pass fibers to obtain ≈5 nm control of fundamental mode cutoff wavelength λ_c in performs with random variations in index or cross sections of up to 20%. Without the method such variations cause >100 nm unpredictable shifts in fundamental mode cutoff wavelength λ_c. This advantage can be obtained even when systematic shifts are present.

Fundamental cutoff wavelength λ_c in pulled short-pass fiber **620** can be further adjusted by stressing or coiling fiber **620** in accordance with well-known principles. That is because the fundamental mode cutoff wavelength λ_c gets displaced during coiling of short-pass fiber **620** relative to the fundamental mode cutoff wavelength of short-pass fiber **620** when straight. Meanwhile, the overall shape of roll-off loss curves **640**, as shown in Fig. 38 is basically preserved. Hence, one can use the coiling diameter of short-pass fiber **620** to make fine-tuning adjustments to fundamental mode cutoff wavelength λ_c after short-pass fiber **620** has been drawn from preform **600**. This can be done to compensate for slight errors in selecting the correct drawing ratio DR, or to compensate for slight errors in pulling to an adjusted drawing ratio DR'. This can also be done to compensate for slight shifts in fundamental mode cutoff wavelength λ_c resulting from diffusion of dopants in short-pass fiber **620** during the pulling process, or to compensate for slight variations in the longitudinal portion of refractive index profile **622** of perform **600** along axis **627**.

Alternatively, it is also possible to determine drawing ratio DR with a particular coiling radius in mind. This is frequently the case when short-pass fiber **620** is to be packaged in a box of prescribed dimensions. The effect of coiling on cutoff wavelength λ_c is considered in determining drawing ratio DR in these situations. Specifically, since decreasing the coiling diameter (smaller coil) shifts cutoff wavelength λ_c to shorter wavelengths the amount of shift for the desired coiling diameter has to be added when setting minimum fundamental mode cutoff wavelength λ_m before drawing preform **600**. For example, coiling a fiber at a diameter of 50 nm shifts fundamental mode cutoff wavelength λ_m by about 20 nm to 200 nm as compared with fundamental mode cutoff wavelength λ_m for the same fiber when straight. This shift increases approximately in proportion to the curvature (inverse of the diameter) of the fiber. The magnitude of this shift depends on the mode field diameter (MFD) of the fiber and also depends on the outside diameter (OD) of the fiber. In general, a fiber with a larger MFD is more sensitive to coiling (due to the increased stresses produced for a given bend diameter). The sensitivity to bending of a particular fiber design (i.e., given MFD, OD, etc.) can be measured at the pilot draw stage.

In the embodiments discussed above the cross-sections described by radii r_c, r_{dc} and r_{sc} in preform **600** exhibit only small variation along the length of preform **600** or along axis **627** and hence do not cause significant variations of final cross-sections described by radius r_o or radii r_1, r_2 in pulled short-pass fiber **620** along axis **627**. In fact, when the variations in drawing ratio DR, radii and indices (i.e., the corresponding tolerances in DR, radii and indices) remain within .3% in preform **600** the resulting pulled fiber will have sufficient performance to amplify signals in the S-band. For other bands, such as the C- and L-bands the tolerances are even greater.

A person skilled in the art will realize that the method of invention can be employed for pulling any type of short-pass fiber. In particular, it is possible to pull fibers with active cores, e.g., Er or Tm doped cores. The same steps as described above can be used in pulling such fibers, and the additional effects on the refractive indices introduced by the active dopants will typically be automatically included in the measurements of refractive index profile and fundamental mode cutoff wavelength λ_c.

It will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

CLAIMS

1. A fiber amplifier comprising:
   a) a core having a core cross-section and a refractive index n_o;
   b) an active material doped in said core;
   c) a depressed cladding surrounding said core, said depressed cladding having a depressed cladding cross-section and a refractive index n_1;
   d) a secondary cladding surrounding said depressed cladding, said secondary cladding having a secondary cladding cross-section and a refractive index n_2;
   e) a pump source for pumping said active material to a high relative inversion D, such that said active material exhibits positive gains in a short wavelength band and high gains in a long wavelength band;

   wherein said core cross-section, said depressed cladding cross-section, and said refractive indices n_o, n_1, and n_2 are selected to produce a roll-off loss curve about a cutoff wavelength λ_c, said roll-off loss curve yielding losses at least comparable to said high gains in said long wavelength band and losses substantially smaller than said positive gains in said short wavelength band.

2. The fiber amplifier of claim 1, wherein said refractive index n_o is selected such that an effective index experienced by a mode of radiation confined in said core is selected to provide a roll-off slope of said roll-off loss curve before said cutoff wavelength λ_c that is greater than or about equal to the maximum slope of the gain spectrum in said long wavelength band.

3. The fiber amplifier of claim 2, wherein said refractive index n_o is selected such that the slope of said effective index with respect to said cutoff wavelength λ_c is in the range of .002/1000 nm to .008/1000 nm.

4. The fiber amplifier of claim 2, wherein said refractive index n_o is at least 0.5% larger than said refractive index n_2.

5. The fiber amplifier of claim 1, wherein said cutoff wavelength λ_c is contained in said long wavelength band.

6. The fiber amplifier of claim 1, wherein said cutoff wavelength λ_c is contained in said short wavelength band.

7. The fiber amplifier of claim 1, wherein said cutoff wavelength λ_c is between said short wavelength band and said long wavelength band.

8. The fiber amplifier of claim 1, wherein said active material is Erbium.

9. The fiber amplifier of claim 8, wherein said short wavelength band comprises at least a portion of the S-band and said long wavelength band comprises at least a portion of the C-band or L-band.

10. The fiber amplifier of claim 9, wherein said cutoff wavelength λ_c is set near 1525 nm.

11. The method of claim 9, wherein said roll-off loss curve is selected to yield losses in said S-band smaller by at least 5 dB than said positive gains.

12. The fiber amplifier of claim 8, wherein said fiber comprises a silicate-containing glass.

13. The fiber amplifier of claim 12, wherein said silicate-containing glass is selected from the group of alumino-germanosilicate glass and phosphorus doped germanosilicate glass.

14. The fiber amplifier of claim 8, wherein said active material is Erbium with a concentration of about 0.1% wt in said core.

15. The fiber amplifier of claim 8, wherein said pump source is a laser diode providing pumping radiation at about 980 nm.

16. The fiber amplifier of claim 1, wherein said refractive index n_o of said core differs from said refractive index n_2 of said secondary cladding by about 0.005 to about 0.03.

17. The fiber amplifier of claim 1, wherein said refractive index n_1 of said depressed cladding differs from said refractive index n_2 of said secondary cladding by about -0.004 to about -0.02.

18. The fiber amplifier of claim 1, wherein said core cross-section and said depressed cladding cross-section are selected from the shapes consisting of circles, ellipses and polygons.

19. The fiber amplifier of claim 1, wherein said pump source provides pump radiation at an intensity sufficient to ensure that said high relative inversion $D \geq 0.7$.

20. The method of claim 1, wherein said roll-off loss curve is selected to yield losses of at least 100 dB in said long wavelength band.

21. A method for designing a fiber amplifier using an active material pumped to a high relative inversion D, said active material exhibiting positive gains in a short wavelength band and high gains in a long wavelength band, said method comprising:

a) providing a core having a core cross-section and a refractive index n_o;

b) doping said active material into said core;

c) providing a depressed cladding around said core, said depressed cladding having a depressed cladding cross-section and a refractive index n_1;

d) providing a secondary cladding around said depressed cladding, said secondary cladding having a secondary cladding cross-section and a refractive index n_2;

e) selecting said core cross section, said depressed cladding cross-section, and said refractive indices n_o, n_1, and n_2 to produce a roll-off loss curve about a cutoff wavelength λ_c, said roll-off loss curve yielding losses at least comparable to said high gains in said long wavelength band and losses substantially smaller than said positive gains in said short wavelength band.

22. The method of claim 21, wherein said refractive index n_o is selected such that an effective index experienced by a

mode of radiation confined in said core is selected to provide a roll-off slope of said roll-off loss curve before said cutoff wavelength λ_c that is greater than or about equal to the maximum slope of the gain spectrum in said long wavelength band.

23. The method of claim 22, wherein said refractive index n_o is selected such that the slope of said effective index with respect to said cutoff wavelength λ_c is in the range of .002/1000 nm to .008/1000 nm.

24. The method of claim 22, wherein said refractive index n_o is at least 0.5% larger than said refractive index n_2.

25. The method of claim 21, wherein said cutoff wavelength λ_c is contained in said long wavelength band.

26. The method of claim 21, wherein said cutoff wavelength λ_c is contained in said short wavelength band.

27. The method of claim 21, wherein said cutoff wavelength λ_c is contained between said long wavelength band and said short wavelength band.

28. The method of claim 21, wherein said active material is Erbium, wherein said long wavelength band is at least a portion of the C-band and the L-band, and wherein said short wavelength band is at least a portion of the S-band.

29. The method of claim 28, wherein said roll-off loss curve is selected to yield losses of at least 100 dB in said long wavelength band.

30. The method of claim 28, wherein said roll-off loss curve is selected to yield losses in said S-band smaller by at least 5 dB than said positive gains.

31. The method of claim 21, wherein said high relative inversion D is maintained at $D \geq 0.7$.

32. The method of claim 21, further comprising adjusting a length L of said fiber amplifier to yield a predetermined gain over said short wavelength band.

33. A method for pumping a fiber amplifier in a W-profile fiber, said method comprising:

a) providing a core having a core cross-section and a refractive index n_o;

b) doping an active material into said core;

c) providing a depressed cladding around said core, said depressed cladding having a depressed cladding cross-section and a refractive index n_1;

d) providing a secondary cladding around said depressed cladding, said secondary cladding having a secondary cladding cross-section and a refractive index n_2;

e) selecting said core cross section, said depressed cladding cross-section, and said refractive indices n_o, n_1, and n_2 to produce a roll-off loss curve about a cutoff wavelength λ_c; and

f) pumping said active to a relative inversion $D \geq 0.7$, such that said active material exhibits positive gains in a short wavelength band and high gains in a long wavelength band.

34. The method of claim 33, wherein said active material is Erbium, and said roll-off loss curve yielding losses at least comparable to said high gains in said long wavelength band and losses substantially smaller than said positive gains in said short wavelength band, wherein said long wavelength band is at least a portion of the C-band or the L-band and said short wavelength band is at least a portion of the S-band.

35. The method of claim 34, wherein said refractive index n_o is selected such that an effective index experienced by a mode of radiation confined in said core is selected to provide a roll-off slope of said roll-off loss curve before said cutoff wavelength λ_c that is greater than or about equal to the maximum slope of the gain spectrum in said long wavelength band.

36. The method of claim 35, wherein said refractive index n_o is selected such that the slope of said effective index with respect to said cutoff wavelength λ_c is in the range of .002/1000 nm to .008/1000 nm.

37. The method of claim 34, wherein said cutoff wavelength λ_c is contained in said long wavelength band.

38. The method of claim 34, wherein said cutoff wavelength λ_c is contained between said long wavelength band and said short wavelength band.

39. The method of claim 34, wherein said cutoff wavelength λ_c is contained in said S-band.

40. The method of claim 34, wherein said refractive index n_o is at least 0.5% larger than said refractive index n_2.

41. A fiber amplifier comprising:
   a) an active material-doped region wherein said active material is Erbium;
   b) a mechanism for providing a distributed loss by engineering an index profile in said fiber; and
   c) a pump source producing a high inversion, wherein the gain at a wavelength below 1525nm exceeds the distributed loss at said wavelength below 1525nm by at least 5dB, and wherein the distributed loss in a wavelength band longer than 1525nm exceeds the gain in said wavelength band longer than 1525nm.

42. A fiber amplifier comprising:
   a) an active material-doped region wherein said active material is Erbium;
   b) a mechanism for providing a distributed loss; and
   c) a pump source producing a high inversion, wherein the gain at a wavelength below 1525nm exceeds the distributed loss at said wavelength below 1525nm by at least 5dB, and wherein the distributed loss in a wavelength band longer than 1525nm exceeds the gain in said wavelength band longer than 1525nm.

43. The fiber of claim 42, wherein said distributed loss is by engineering an index profile in said fiber.

44. A fiber amplifier with suppressed cladding mode loss, said fiber amplifier comprising:
   a) an active core;
   b) a cladding surrounding said active core;
   c) an index profile established in said active core and in said cladding such that said active core exhibits a loss above a cutoff wavelength λ_c and positive

gains in a short wavelength range below said cutoff wavelength λ_c;

d) a means for suppressing coupling of a radiation in said short wavelength range between said active core and said cladding.

45. The fiber amplifier of claim 44, wherein said means for suppressing coupling comprises a material distributed in said cladding, said material being selected from the group consisting of scattering materials and absorbing materials.

46. The fiber amplifier of claim 45, wherein said cladding comprises a depressed cladding having a depressed cladding cross-section and a refractive index n_1, and a secondary cladding having a secondary cladding cross-section and a refractive index n_2, and said material is distributed in said secondary cladding.

47. The fiber amplifier of claim 45, wherein said radiation has a mode diameter extending from said active core into said cladding, and said material is distributed outside said mode diameter.

48. The fiber amplifier of claim 45, wherein said absorbing material comprises a rare earth element.

49. The fiber amplifier of claim 44, wherein said means for suppressing coupling comprises a non-phase-matched length section of said fiber amplifier, such that the coupling of said radiation is not phase matched between said core and said cladding.

50. The fiber amplifier of claim 49, wherein said core has a core cross-section and a refractive index n_o, said cladding has a cladding cross-section and a refractive index n_c, and said non-phase-matched length section is formed by a predetermined selection of said core cross-section, cladding cross-section and refractive indices n_o, n_{clad}.

51. The fiber amplifier of claim 49, wherein said cladding comprises a depressed cladding having a depressed cladding cross-section and a refractive index n_1, and a secondary cladding having a secondary cladding cross-section and a refractive index n_2.

52. The fiber amplifier of claim 51, wherein said core has a core cross-section and a refractive index n_o, and said non-phase-matched length section is formed by a predetermined selection of said core cross-section, said depressed cladding cross-section, said secondary cladding cross section and refractive indices n_o, n_1, n_2.

53. The fiber amplifier of claim 52, wherein said cladding further comprises an outer cladding having an outer cladding cross-section and a refractive index n_3, where $n_3<n_2$.

54. The fiber amplifier of claim 44, wherein said active core comprises Erbium.

55. The fiber amplifier of claim 54, wherein said cutoff wavelength λ_c is set near 1525 nm.

56. The fiber amplifier of claim 54, further comprising a pump source for pumping said core with radiation at a pump wavelength near 980 nm.

57. A method for suppressing a cladding mode loss in a fiber amplifier having an active core and a cladding surrounding said active core, said method comprising:

a) establishing an index profile in said active core and in said cladding such that said active core exhibits a loss above a cutoff wavelength λ_c and positive gains in a short wavelength range below said cutoff wavelength λ_c; and

b) suppressing coupling of a radiation in said short wavelength range between said active core and said cladding.

58. The method of claim 57, wherein said step of suppressing coupling is performed by distributing a material in said cladding for scattering or absorbing said radiation.

59. The method of claim 58, wherein said radiation has a mode diameter extending from said active core into said cladding, and said material is distributed outside said mode diameter.

60. The method of claim 57, wherein said step of suppressing coupling is performed by preventing phase matching, such that the coupling of said radiation is not phase matched between said core and said cladding.

61. The method of claim 60, wherein phase matching is prevented by selecting a core cross-section and refractive index n_o for said core, and by selecting a

cladding cross section and refractive index n_{clad} for said cladding.

62. The method of claim 60, wherein said core has a core cross section and a refractive index n_o, said cladding comprises a depressed cladding having a depressed cladding cross-section and a refractive index n_1, and a secondary cladding having a secondary cladding cross-section and a refractive index n_2, and wherein said phase matching is prevented by selecting said core cross-section, said depressed cladding cross-section, said secondary cladding cross section and refractive indices n_o, n_1, n_2.

63. The method of claim 62, wherein said cladding further comprises an outer cladding having an outer cladding cross section and a refractive index n_3, where $n_3<n_2$.

64. A source of light in an S-band of wavelengths comprising:

a) a fiber having:

1) a core doped with Erbium and having a core cross-section and a refractive index n_o;

2) a depressed cladding surrounding said core, said depressed cladding having a depressed cladding cross-section and a refractive index n_1; and

3) a secondary cladding surrounding said depressed cladding, said secondary cladding having a secondary cladding cross-section and a refractive index n_2; and

b) a pump source for pumping said Erbium contained in said core to a high relative inversion D, such that said Erbium exhibits positive gains in said S-band

and high gains in a long wavelength band longer than said S-band;

wherein said core cross-section, said depressed cladding cross-section, and said refractive indices n_o, n_1, and n_2 are selected to produce losses at least comparable to said high gains in said long wavelength band and losses substantially smaller than said positive gains in said S-band.

65. The source of claim 64, further comprising a wavelength-selecting means for selecting an output wavelength of said light.

66. The source of claim 65, wherein said wavelength-selecting means comprises a wavelength-selecting feedback mechanism.

67. The source of claim 66, wherein said wavelength-selecting feedback mechanism comprises a fiber Bragg grating.

68. The source of claim 65, wherein said wavelength-selecting means consists of a filter selected from the group consisting of tilted etalons, strain-tuned fiber Bragg gratings, temperature-tuned fiber Bragg gratings, interferometers, arrays waveguide gratings, diffraction gratings and tunable coupled cavity reflectors.

69. The source of claim 65, wherein said wavelength-selecting means comprises a pump source adjustment for tuning said high relative inversion D.

70. The source of claim 65, wherein said wavelength-selecting means comprises a coiling diameter of said fiber.

71. The source of claim 70, wherein said coiling diameter is continuously variable.

72. The source of claim 64, further comprising a master oscillator for seeding said fiber.

73. The source of claim 72, wherein said master oscillator is an optical source selected from the group consisting of distributed feedback laser, Fabry-Perot laser, external cavity diode laser, distributed Bragg reflector laser, vertical cavity surface emitting laser, semiconductor laser, a fiber laser, a broadband source.

74. The source of claim 64, wherein said fiber comprises:
a) a first section having a first coiling diameter; and
b) a second section having a second coiling diameter larger than said first coiling diameter.

75. The source of claim 74, wherein said first section is positioned before said second section for seeding said second section.

76. The source of claim 75, further comprising an isolator installed between said first section and said second section.

77. The source of claim 64, wherein said fiber comprises:
a) a first section wherein said core cross-section, said depressed cladding cross-section, and said refractive indices n_o, n_1, and n_2 are selected to produce a first cutoff wavelength λ_{c1}; and

b) a second section wherein said core cross-section, said depressed cladding cross-section, and said refractive indices n_o, n_1, and n_2 are selected to produce a second cutoff wavelength λ_{c2} longer than said first cutoff wavelength λ_{c1}.

78. The source of claim 77, wherein said first section is positioned before said second section for seeding said second section.

79. The source of claim 78, further comprising an isolator installed between said first section and said second section.

80. The source of claim 64, wherein said pump source comprises a laser diode providing pump light at about 980 nm.

81. The source of claim 64, further comprising an optical cavity for containing said fiber.

82. The source of claim 81, wherein said optical cavity is a ring cavity.

83. A method for generating light in an S-band of wavelengths comprising:

a) providing a fiber having a core doped with Erbium and having a core cross-section and a refractive index n_o;

b) surrounding said core with a depressed cladding having a depressed cladding cross-section and a refractive index n_1;

c) surrounding said depressed cladding with a secondary cladding having a secondary cladding cross-section and a refractive index n_2; and

d) pumping said active material contained in said core to a high relative inversion D, such that said active material exhibits positive gains in said S-band and high gains in a long wavelength band longer than said S-band;

wherein said core cross-section, said depressed cladding cross-section, and said refractive indices n_o, n_1, and n_2 are selected to produce losses at least comparable to said high gains in said long wavelength band and losses substantially smaller than said positive gains in said S-band.

84. The method of claim 83, wherein said step of pumping comprises counter-propagating pumping.

85. The method of claim 83, further comprising seeding said fiber.

86. The method of claim 85, wherein said fiber comprises a first section and a second section, and said method comprises seeding said second section by said first section.

87. The method of claim 83, wherein said pumping is performed in a pulsed mode.

88. The method of claim 83, wherein said light in said S-band is combined with a light outside said S-band.

89. A fiber amplifier comprising:

a) a core having a core cross-section and a refractive index n_o;

b) an active material doped in said core, wherein said active material is Thulium;

c) a depressed cladding surrounding said core, said depressed cladding having a depressed cladding cross-section and a refractive index n_1;

d) a secondary cladding surrounding said depressed cladding, said secondary cladding having a secondary cladding cross-section and a refractive index n_2; and

e) a pump source for pumping said active material to a high relative inversion D, such that said active material exhibits positive gains in a short wavelength band and high gains in a long wavelength band;

wherein said core cross-section, said depressed cladding cross-section, and said refractive indices n_o, n_1, and n_2 are selected to produce a roll-off loss curve about a cutoff wavelength λ_c, said roll-off loss curve yielding losses at least comparable to said high gains in said long wavelength band and losses substantially smaller than said positive gains in said short wavelength band.

90. The fiber amplifier of claim 89, wherein said short wavelength band is the L-band.

91. The fiber amplifier of claim 89, wherein said short wavelength band is between 1.6 and 1.8 μm.

92. The fiber amplifier of claim 89, wherein said long wavelength band is between 1.7 and 2.1 μm.

93. The fiber amplifier of claim 89, wherein said cutoff wavelength is about 1.7 to 1.9 µm.

94. The fiber amplifier of claim 89, wherein said pump source provides pump radiation having an intensity of at least 30 mW.

95. The fiber amplifier of claim 89, wherein said pump source is a laser diode providing pumping radiation at about 1.48 to 1.5 µm.

96. The fiber amplifier of claim 95, wherein said pump source provides pump radiation having an intensity of at least 100 mW.

98. The fiber amplifier of claim 89, wherein said fiber comprises a silicate-containing glass.

99. The fiber amplifier of claim 98, wherein said silicate-containing glass is selected from the group of alumino-germanosilicate glass and phosphorus doped germanosilicate glass.

100. The fiber amplifier of claim 89, wherein said core cross-section and said depressed cladding cross-section are selected from the shapes consisting of circles, ellipses and polygons.

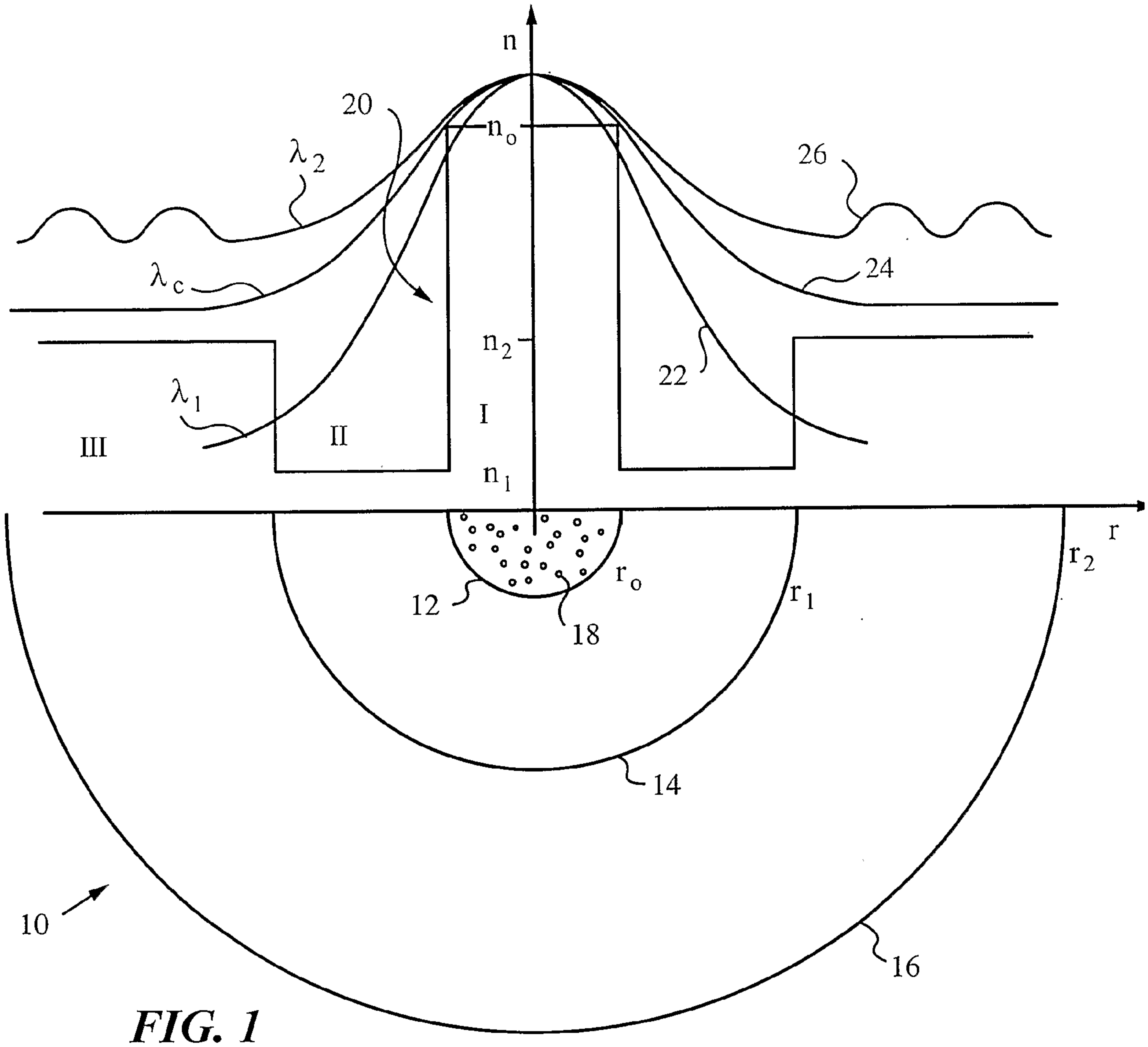

n
20
n_o
λ_2
26
λ_c
24
n_2
22
λ_1
I
II
III
n_1
r
r_2
r_o
r_1
12
18
14
10
16

FIG. 1

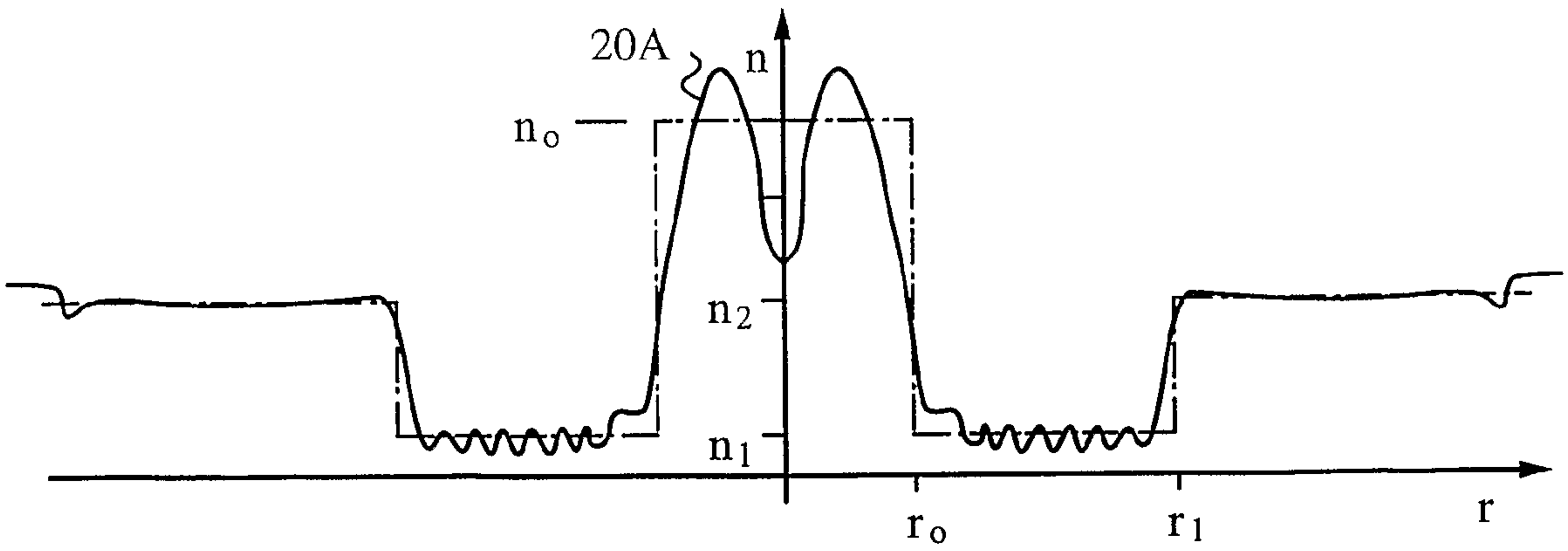

20A
n
n_o
n_2
n_1
r_o
r_1
r

FIG. 2

2/24

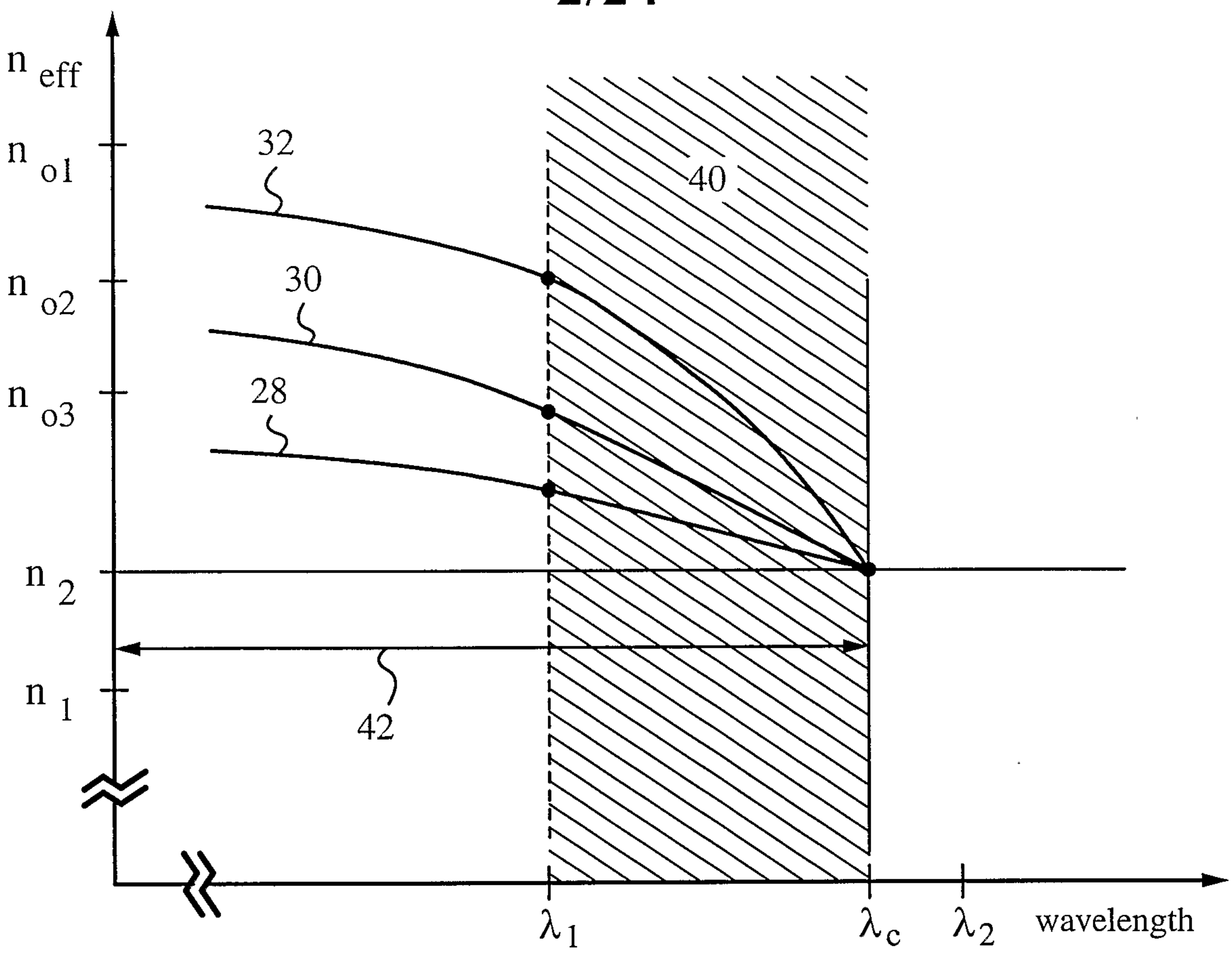


FIG. 3

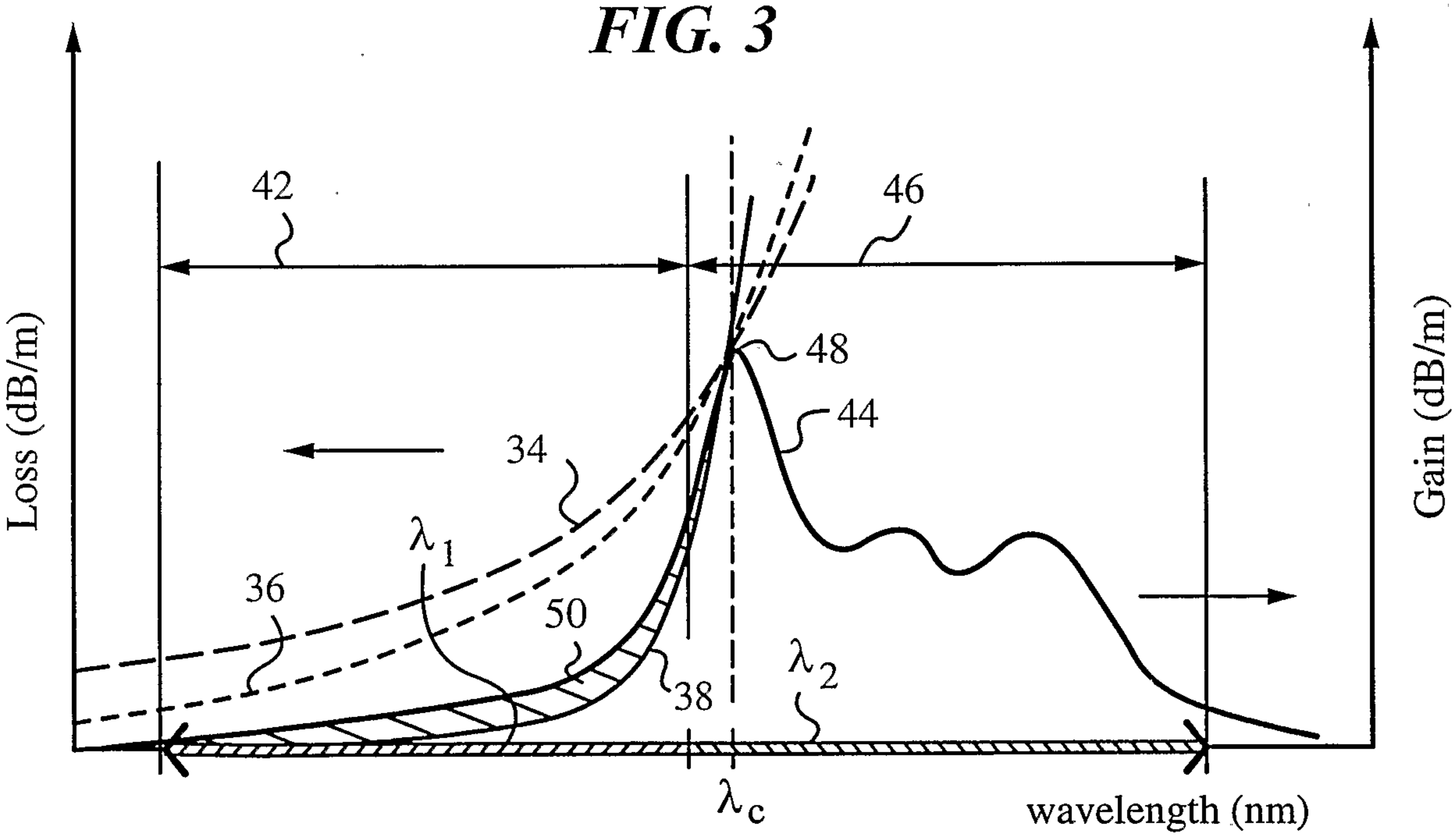


FIG. 4

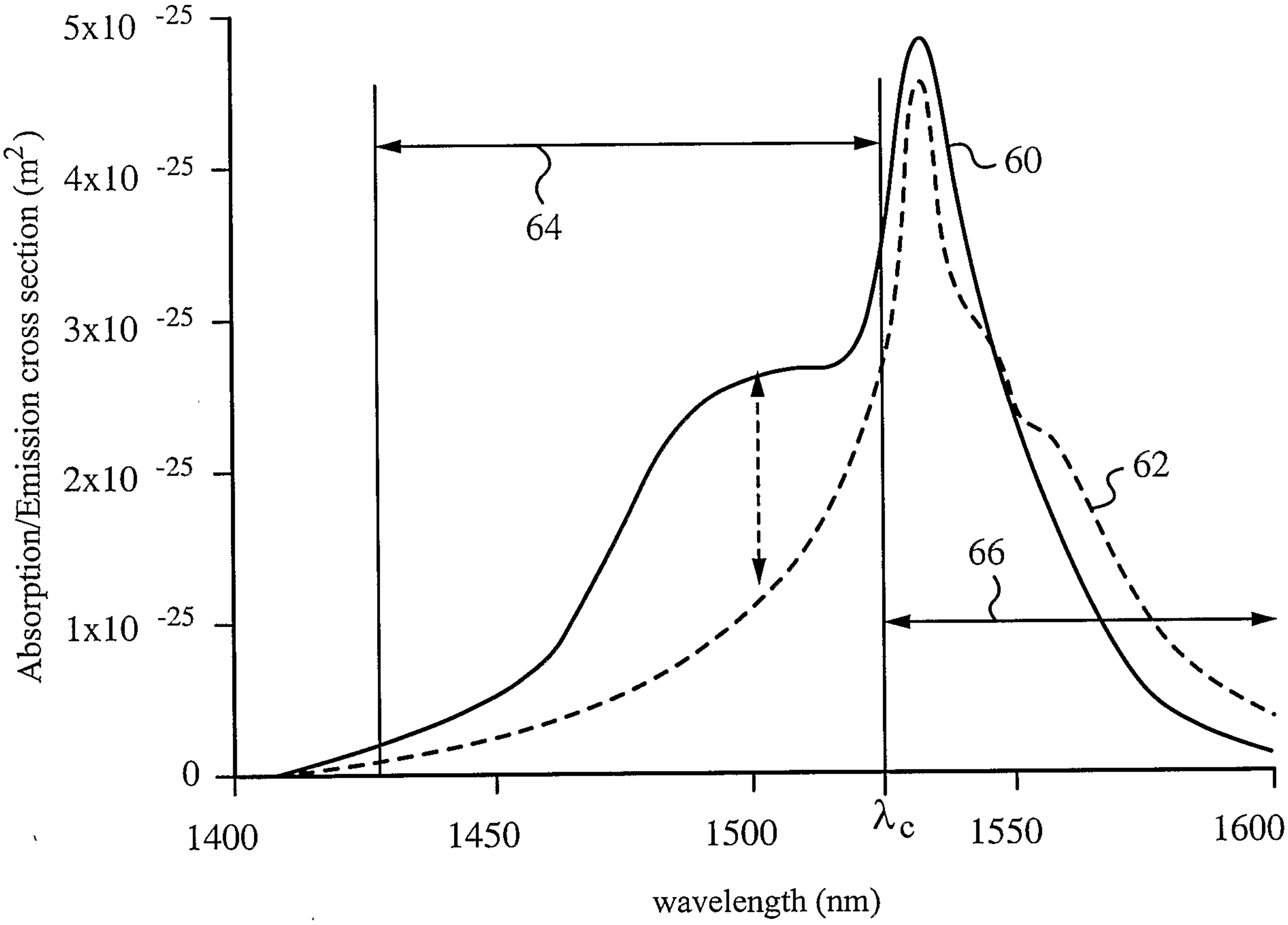

5x10 -25
4x10 -25
3x10 -25
2x10 -25
1x10 -25
0
Absorption/Emission cross section (m2)
64
60
62
66
1400
1450
1500
λc
1550
1600
wavelength (nm)

FIG. 5

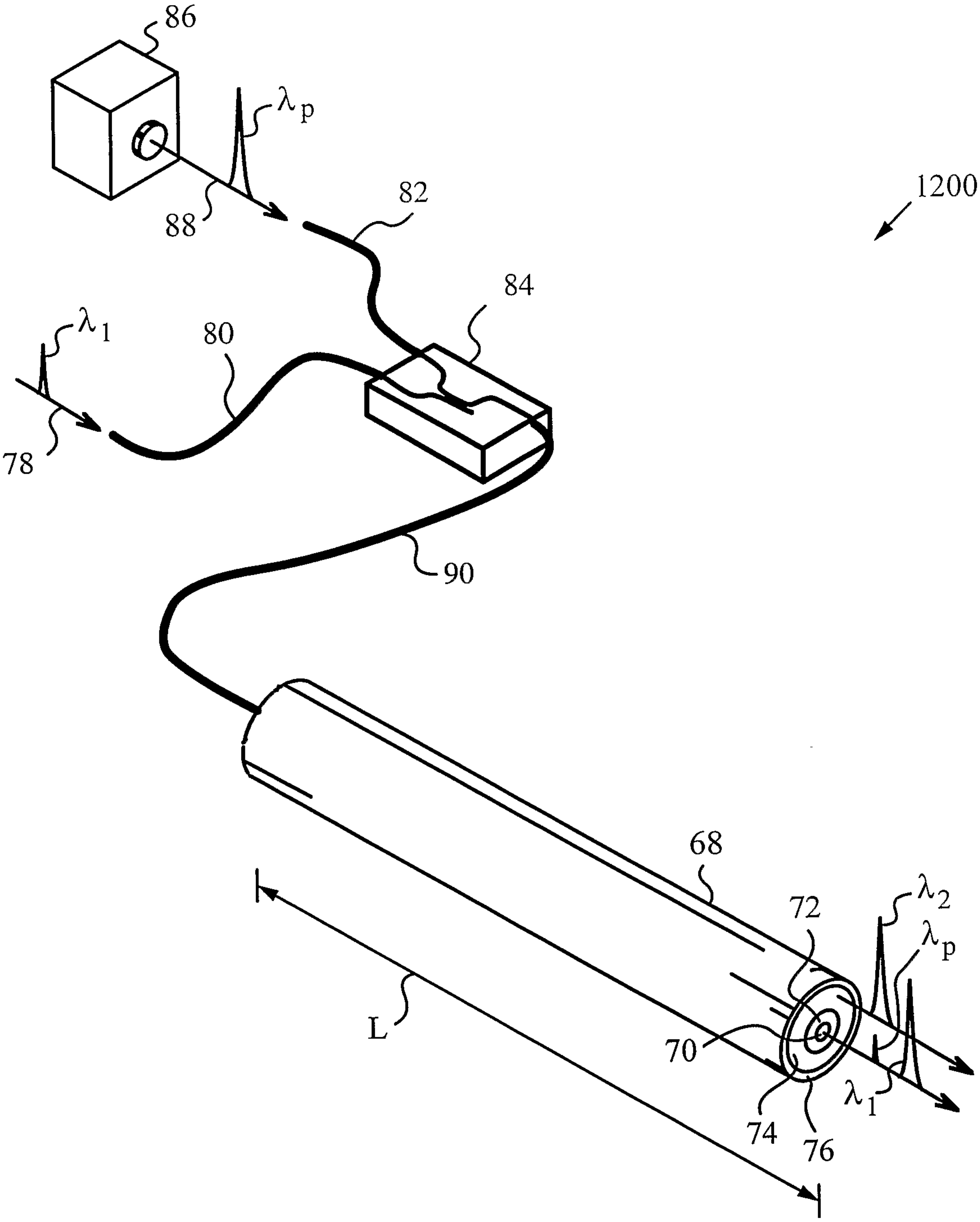


FIG. 6

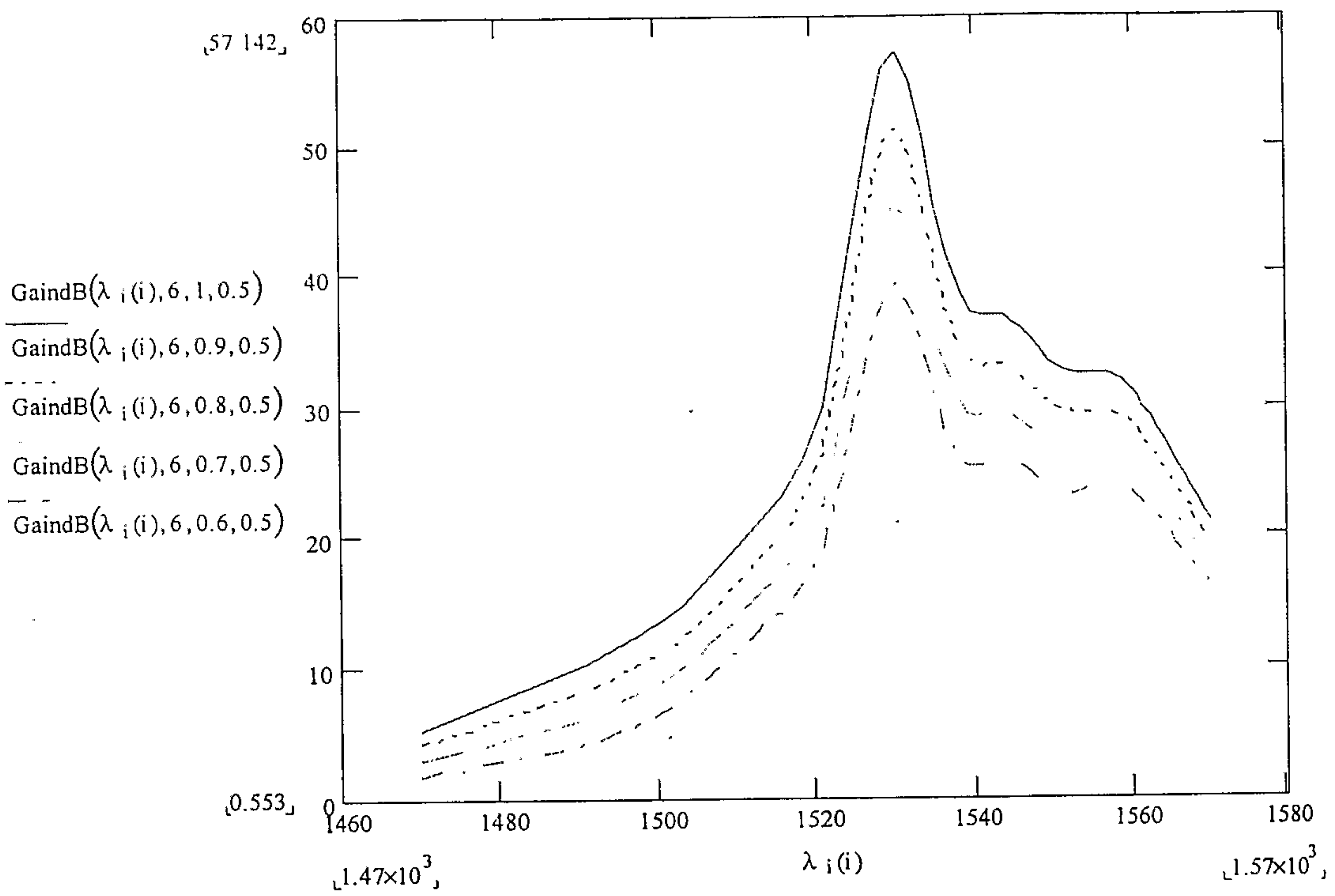

57.142
60
50
40
30
20
10
0
0.553
GaindB(λ i(i), 6, 1, 0.5)
GaindB(λ i(i), 6, 0.9, 0.5)
GaindB(λ i(i), 6, 0.8, 0.5)
GaindB(λ i(i), 6, 0.7, 0.5)
GaindB(λ i(i), 6, 0.6, 0.5)
1460
1480
1500
1520
1540
1560
1580
1.47×10^3
λ i(i)
1.57×10^3

FIG. 7

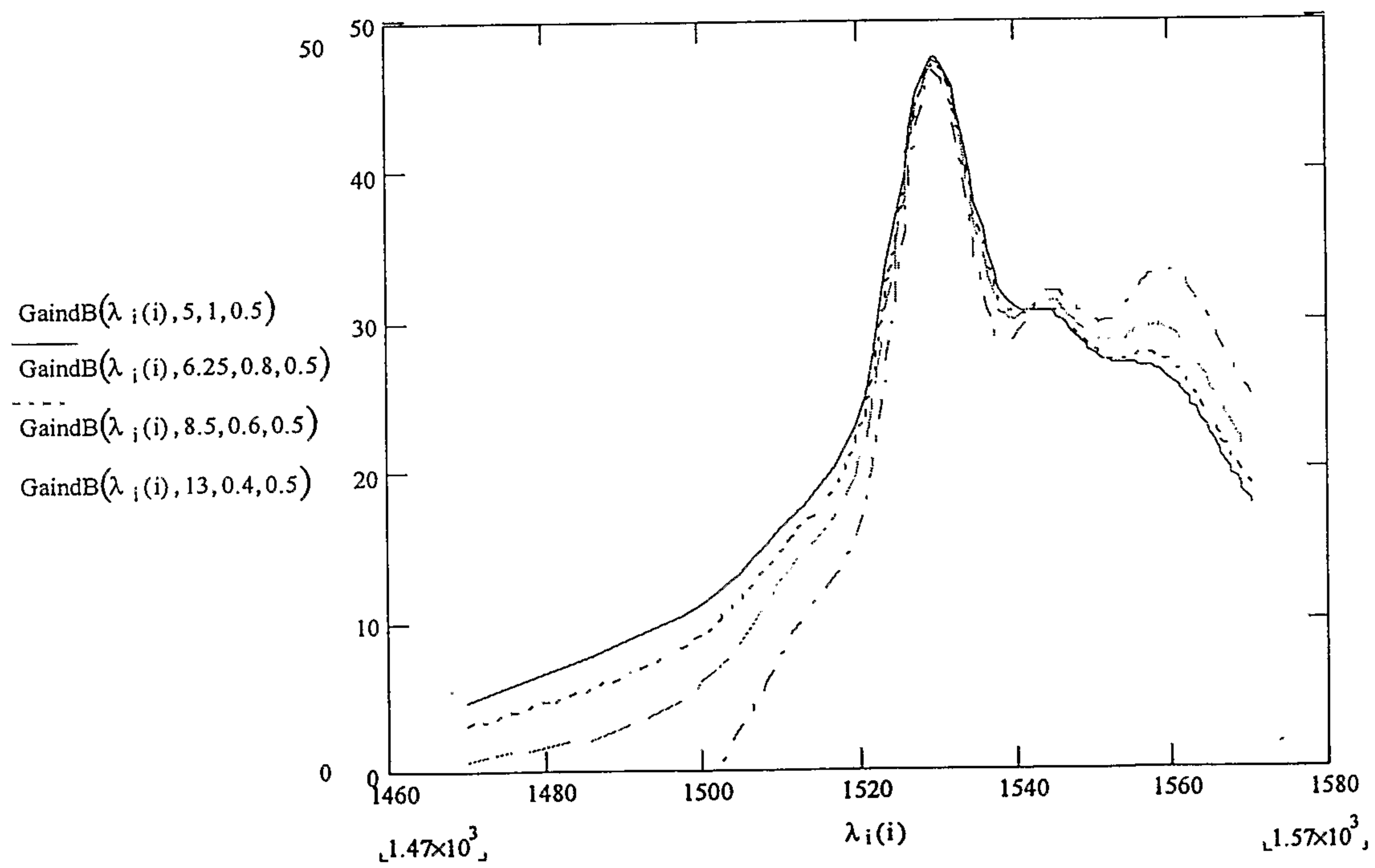

50
50
40
30
20
10
0
0
GaindB(λ i(i), 5, 1, 0.5)
GaindB(λ i(i), 6.25, 0.8, 0.5)
GaindB(λ i(i), 8.5, 0.6, 0.5)
GaindB(λ i(i), 13, 0.4, 0.5)
1460
1480
1500
1520
1540
1560
1580
1.47×10^3
λ i(i)
1.57×10^3

FIG. 8

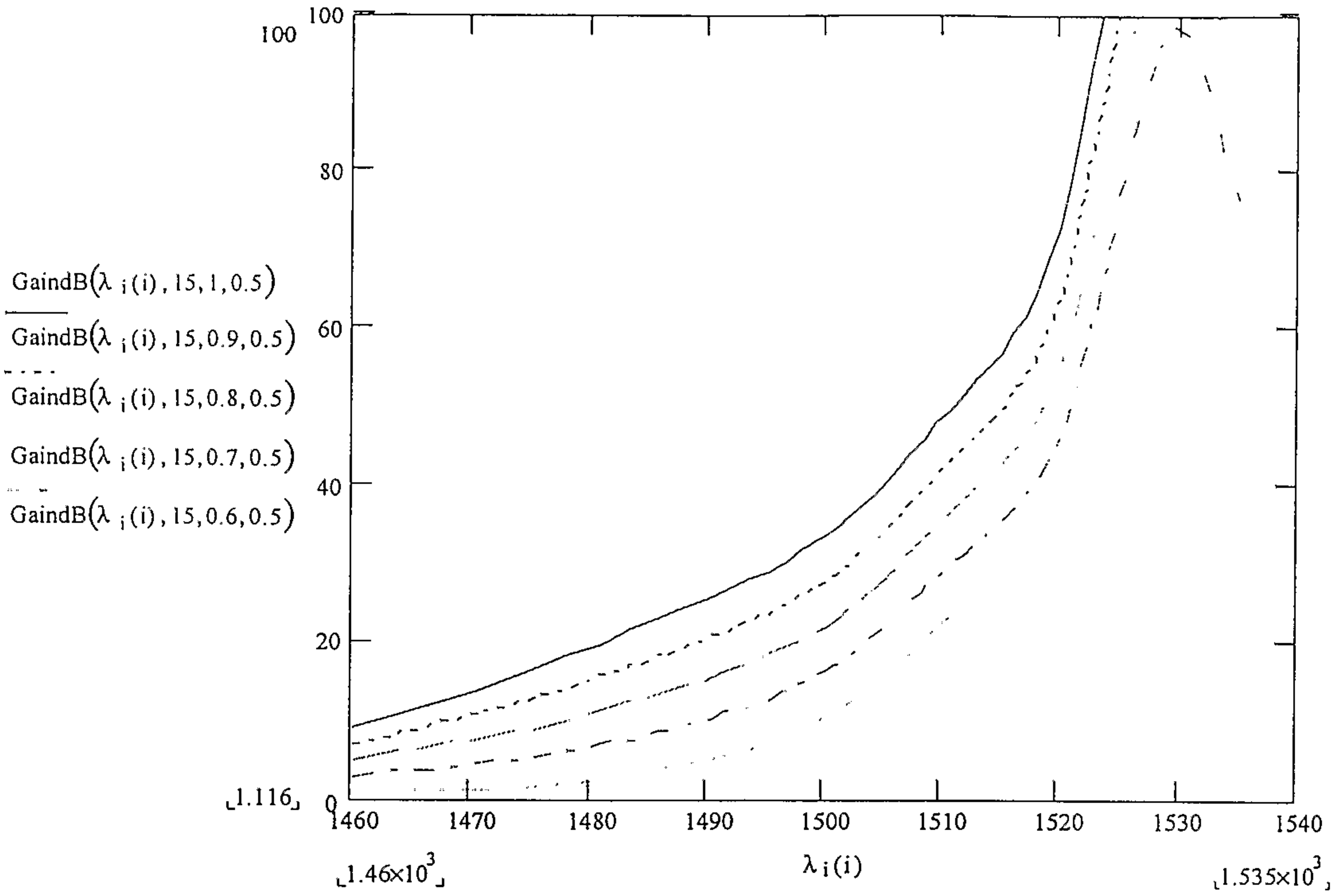

GaindB(λ i(i), 15, 1, 0.5)
GaindB(λ i(i), 15, 0.9, 0.5)
GaindB(λ i(i), 15, 0.8, 0.5)
GaindB(λ i(i), 15, 0.7, 0.5)
GaindB(λ i(i), 15, 0.6, 0.5)
100
80
60
40
20
0
1.116
1460
1470
1480
1490
1500
1510
1520
1530
1540
1.46×10^3
λ i(i)
1.535×10^3

FIG. 9

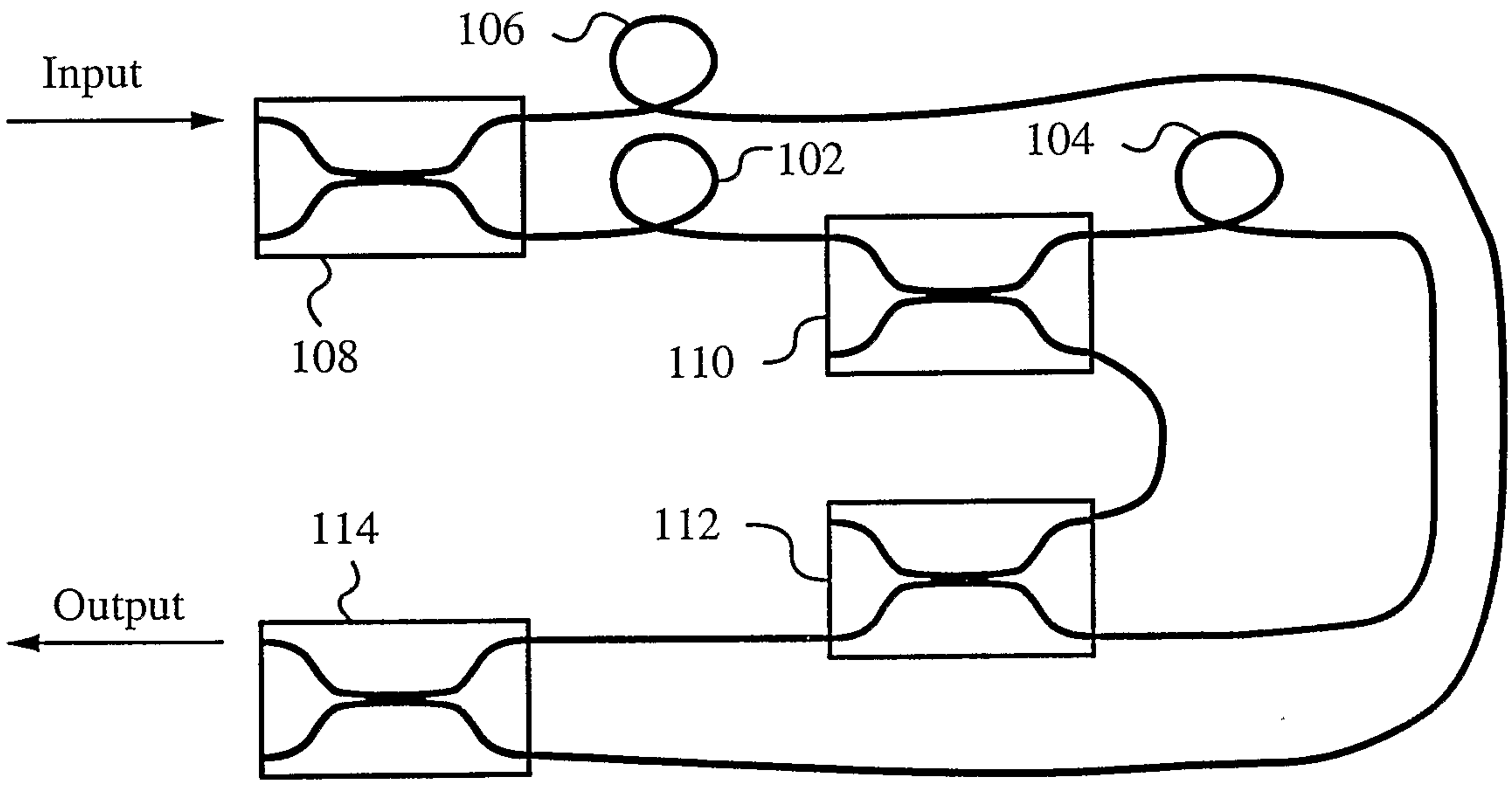

Input
106
102
104
108
110
112
114
Output

FIG. 10

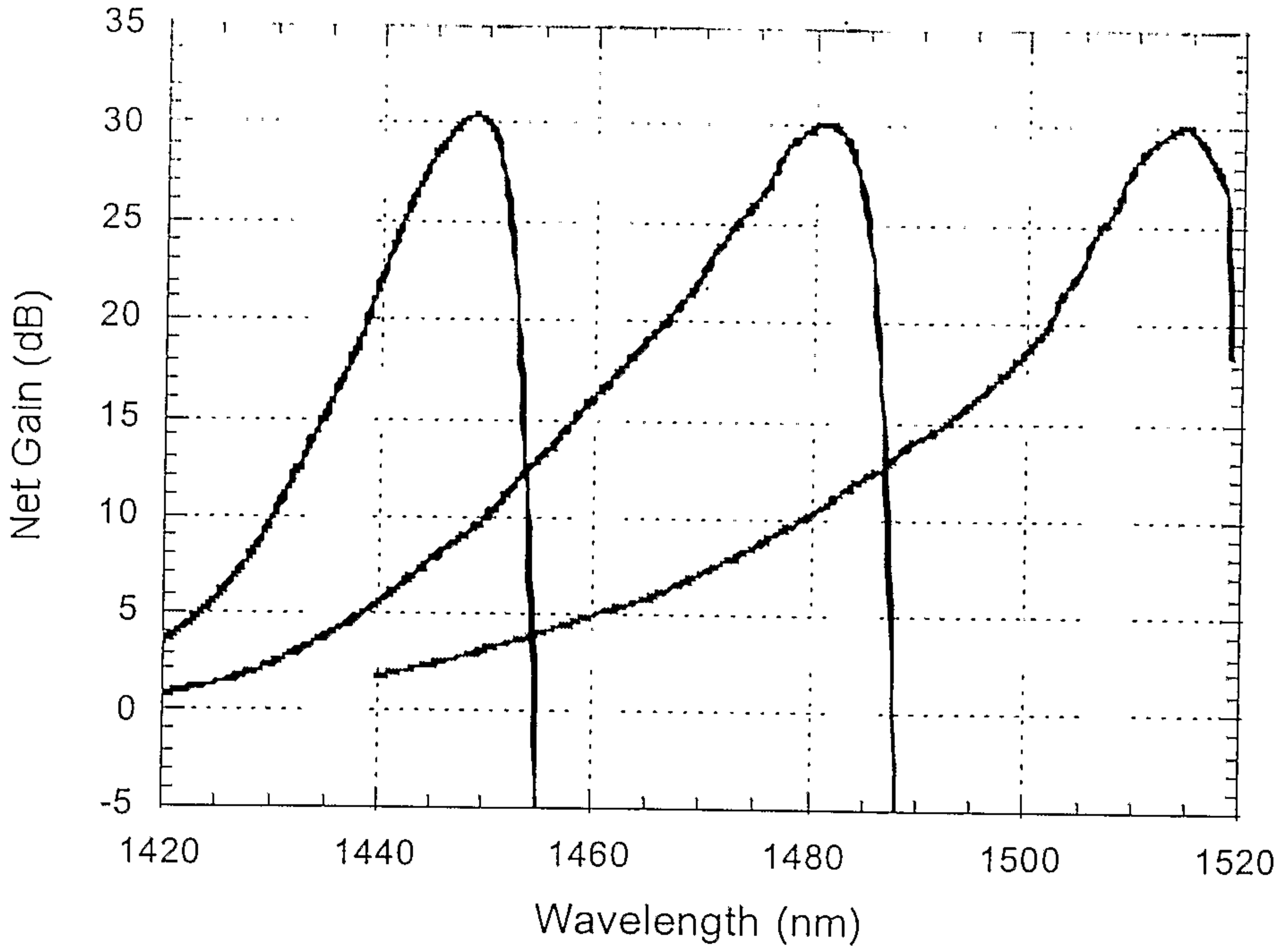

35
30
25
20
15
10
5
0
-5
Net Gain (dB)
1420
1440
1460
1480
1500
1520
Wavelength (nm)

FIG. 11

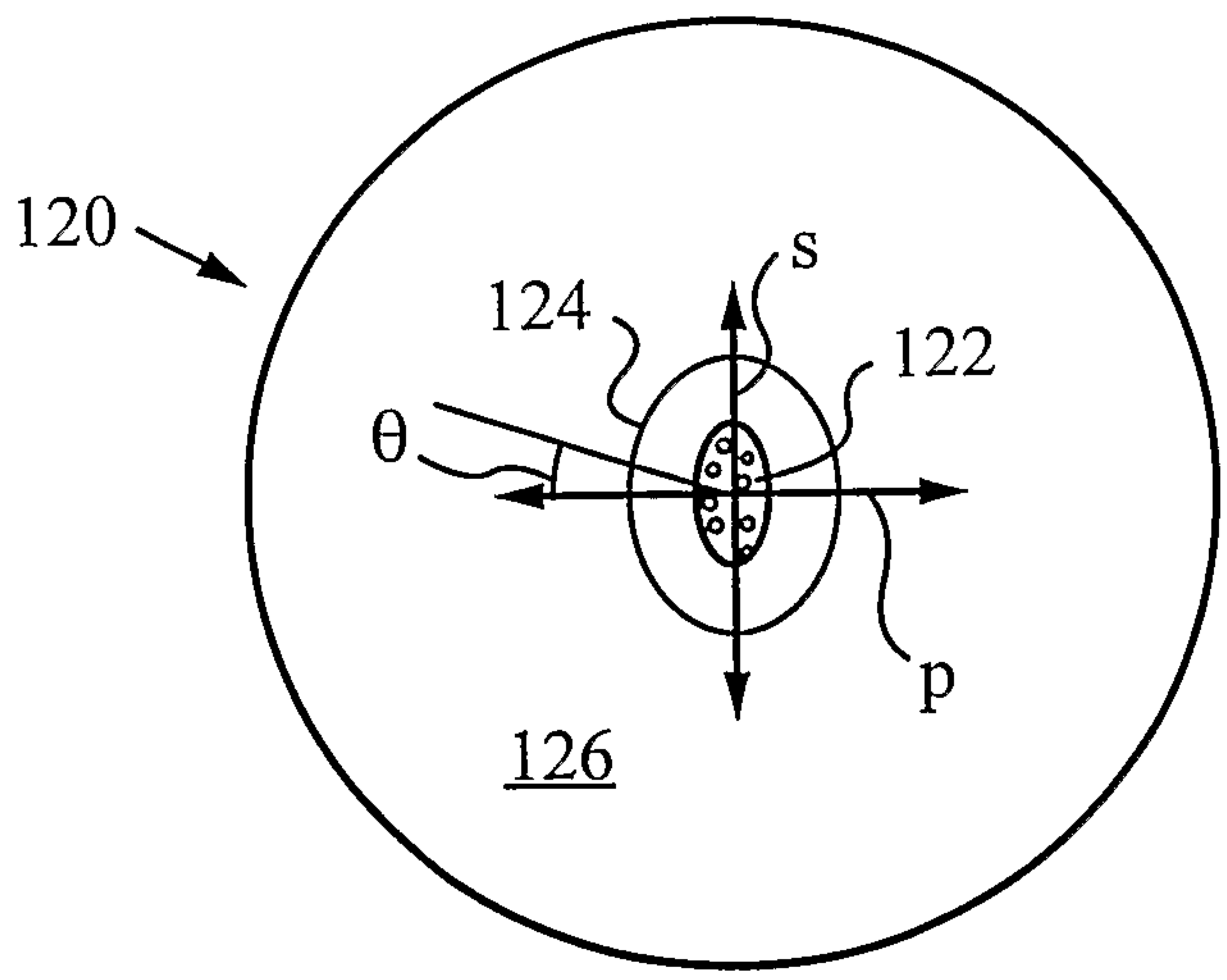

120
124
s
122
θ
p
126

FIG. 12

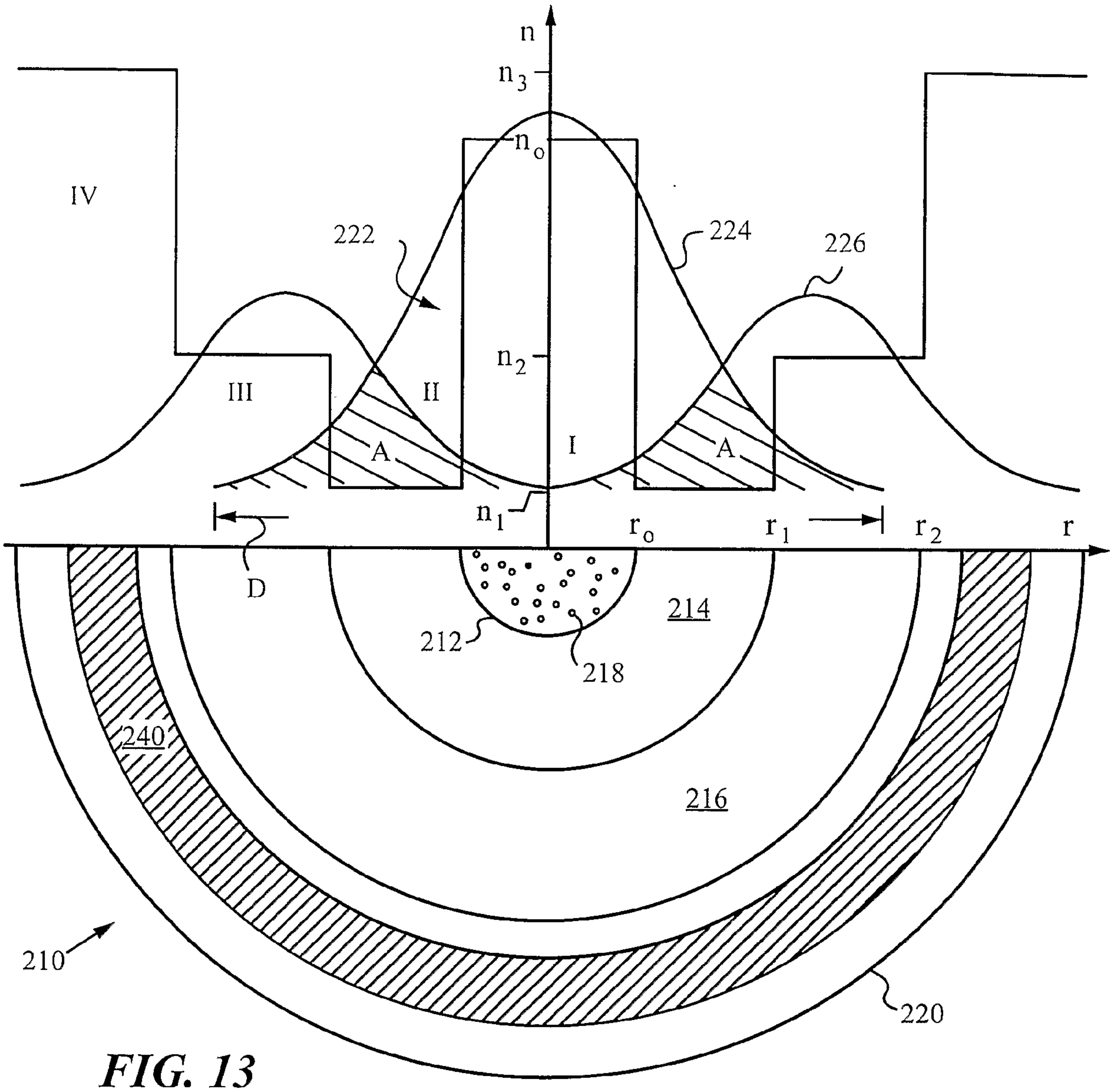

n
n3
n0
IV
222
224
226
n2
III
II
A
I
A
n1
D
r0
r1
r2
r
212
218
214
240
216
210
220

FIG. 13

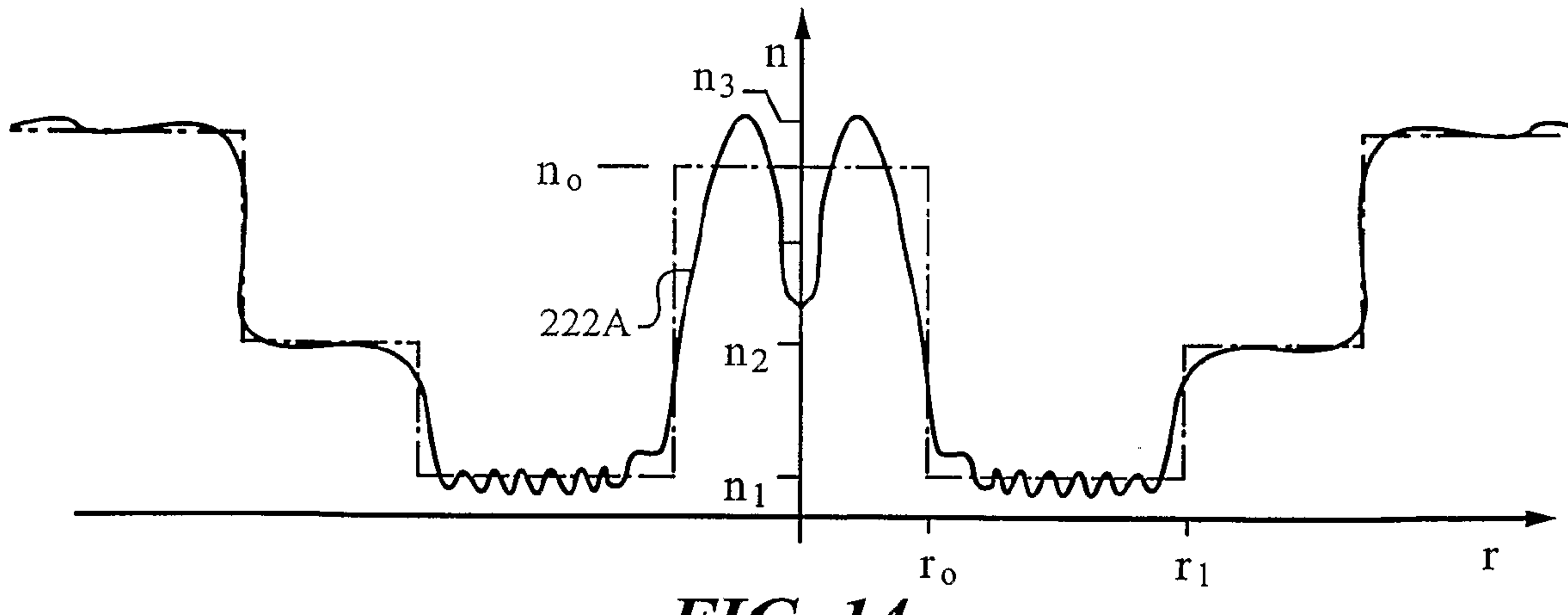

n
n3
n0
222A
n2
n1
r0
r1
r

FIG. 14

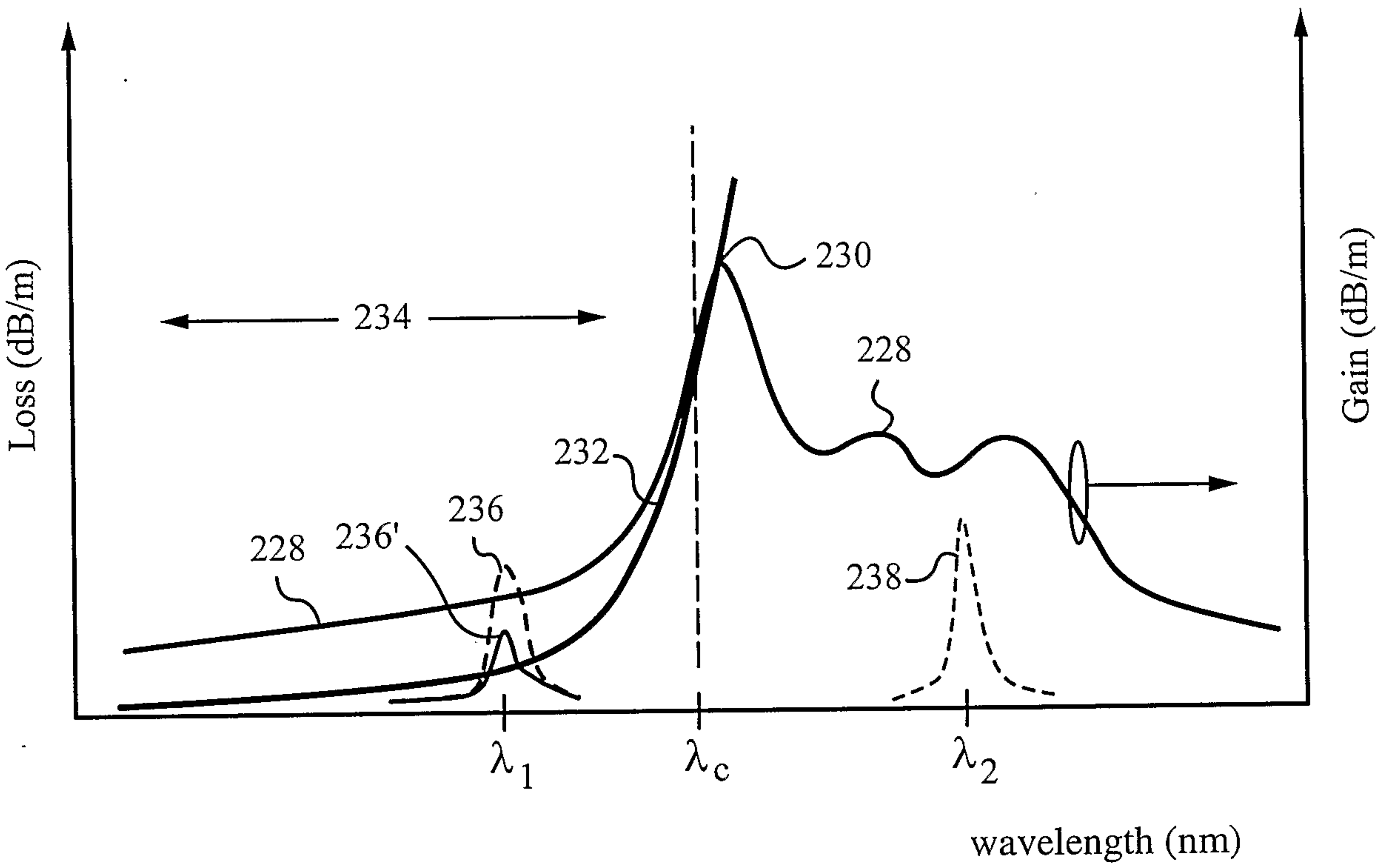

Loss (dB/m)
Gain (dB/m)
234
230
228
232
236
236'
228
238
λ1
λc
λ2
wavelength (nm)

FIG. 15

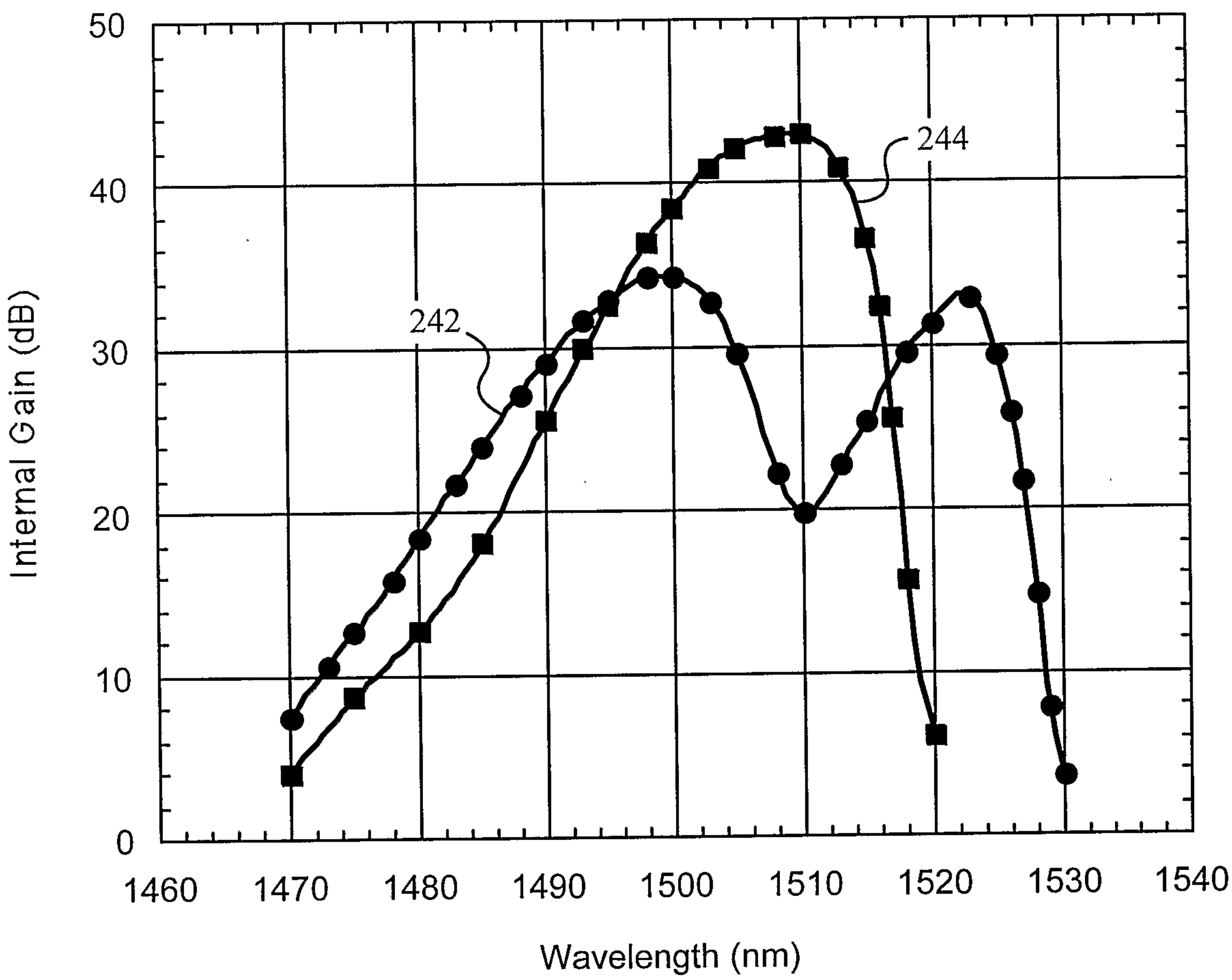

50
40
30
20
10
0
Internal Gain (dB)
1460
1470
1480
1490
1500
1510
1520
1530
1540
Wavelength (nm)
242
244

FIG. 16

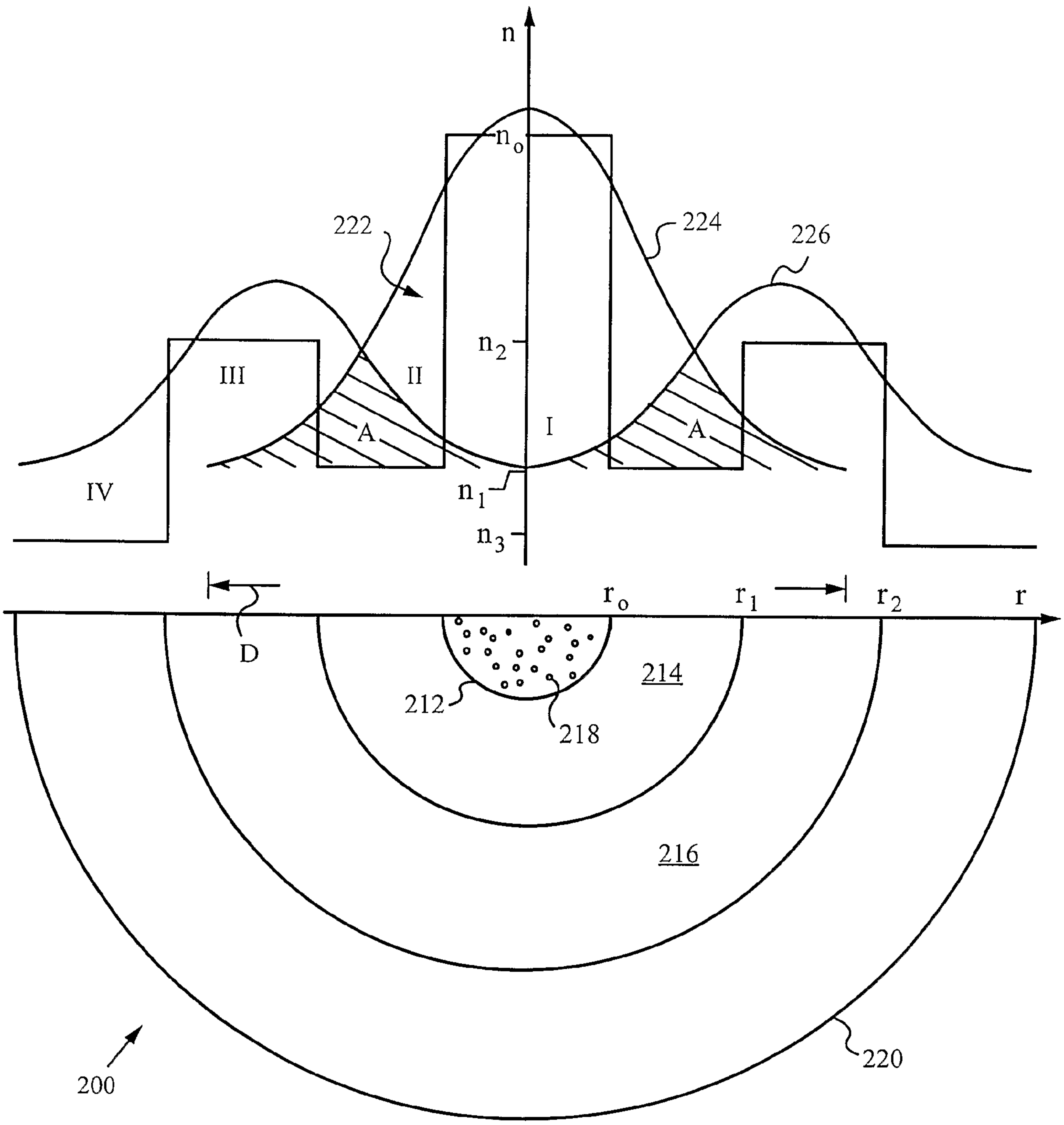

n
n_o
222
224
226
n_2
III
II
A
I
A
IV
n_1
n_3
r_o
r_1
r_2
r
D
214
212
218
216
200
220

FIG. 17

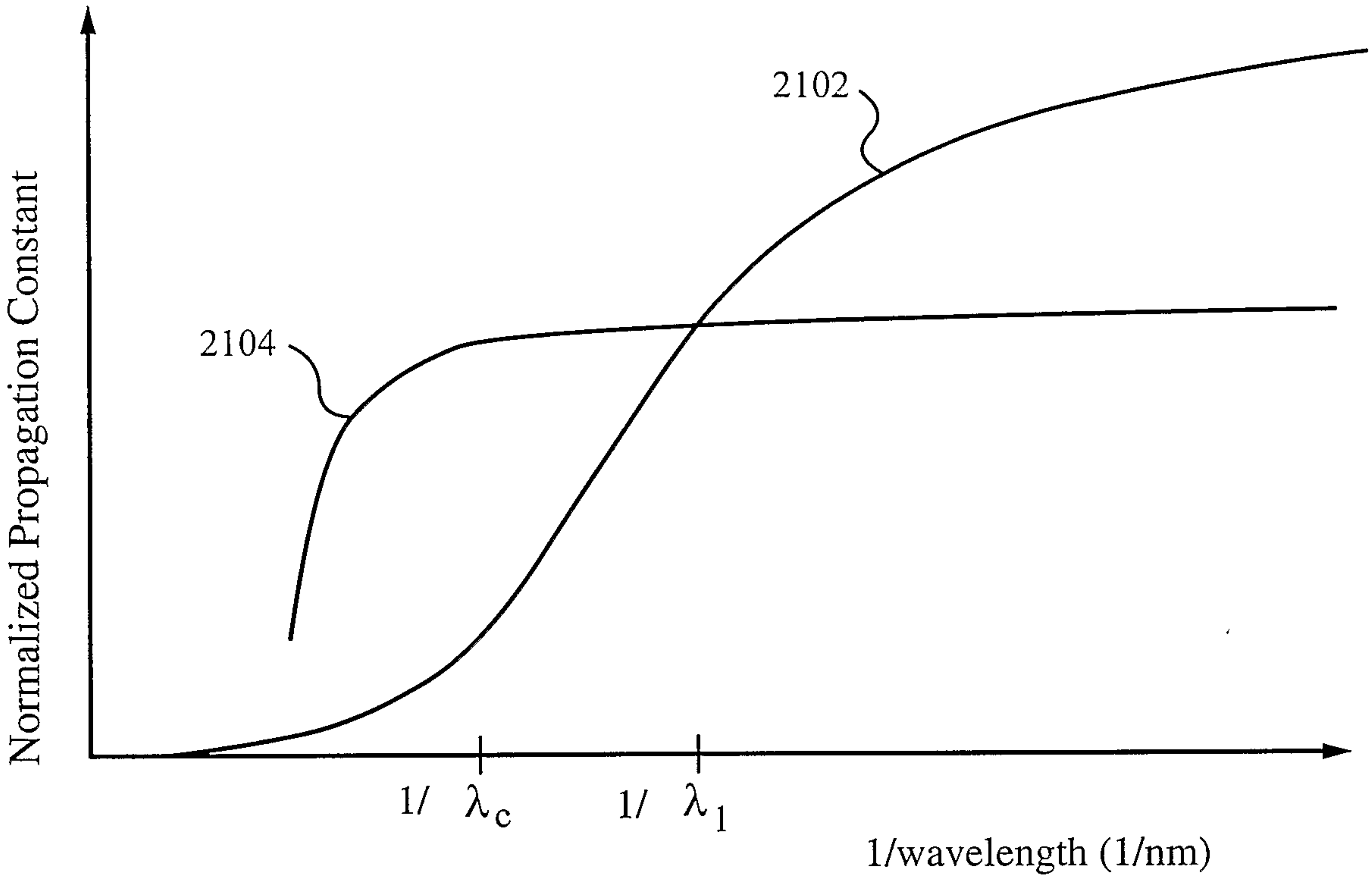

Normalized Propagation Constant
2102
2104
1/ λ_c
1/ λ_1
1/wavelength (1/nm)

FIG. 18

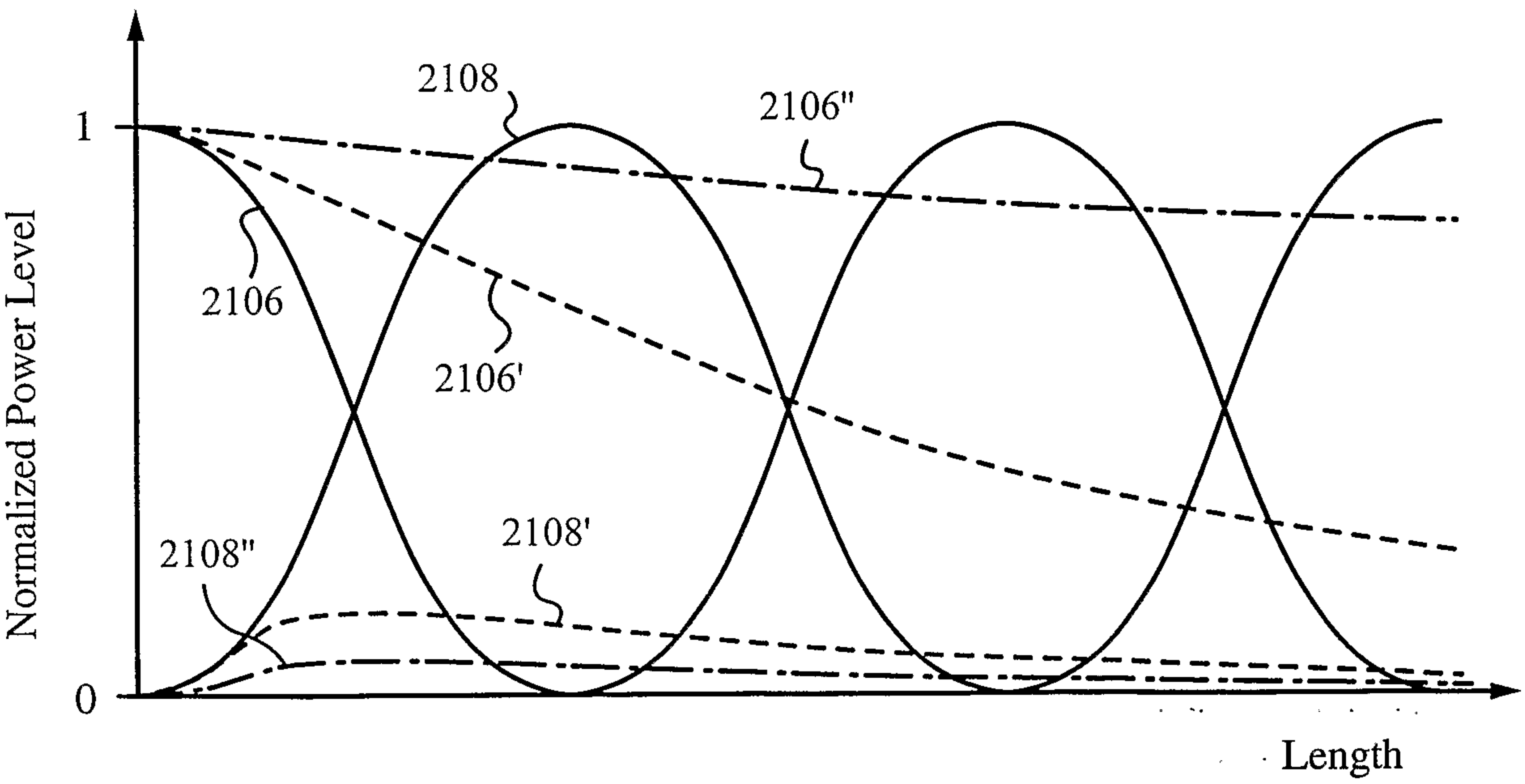

Normalized Power Level
1
0
2108
2106"
2106
2106'
2108'
2108"
Length

FIG. 19

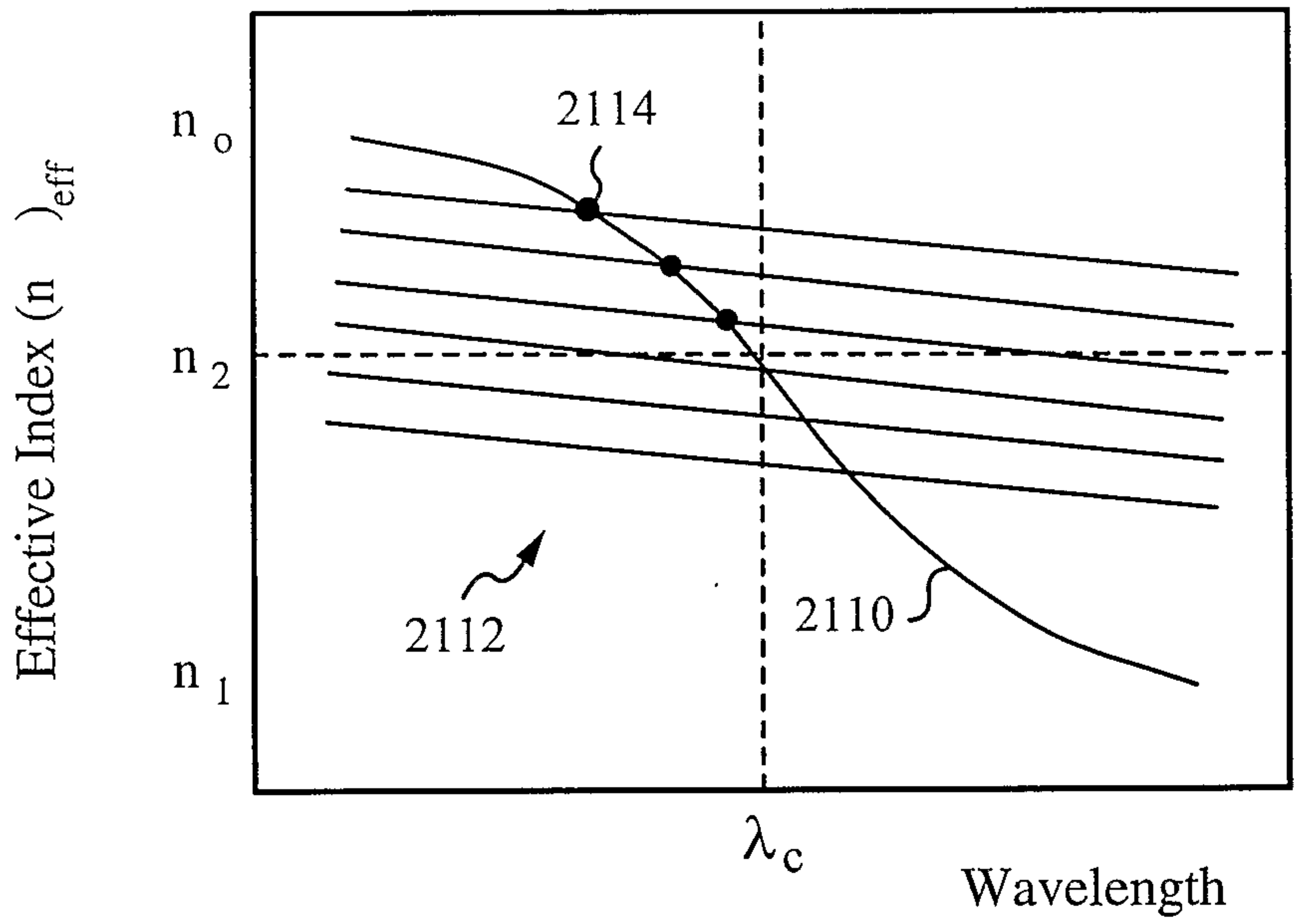


FIG. 20A

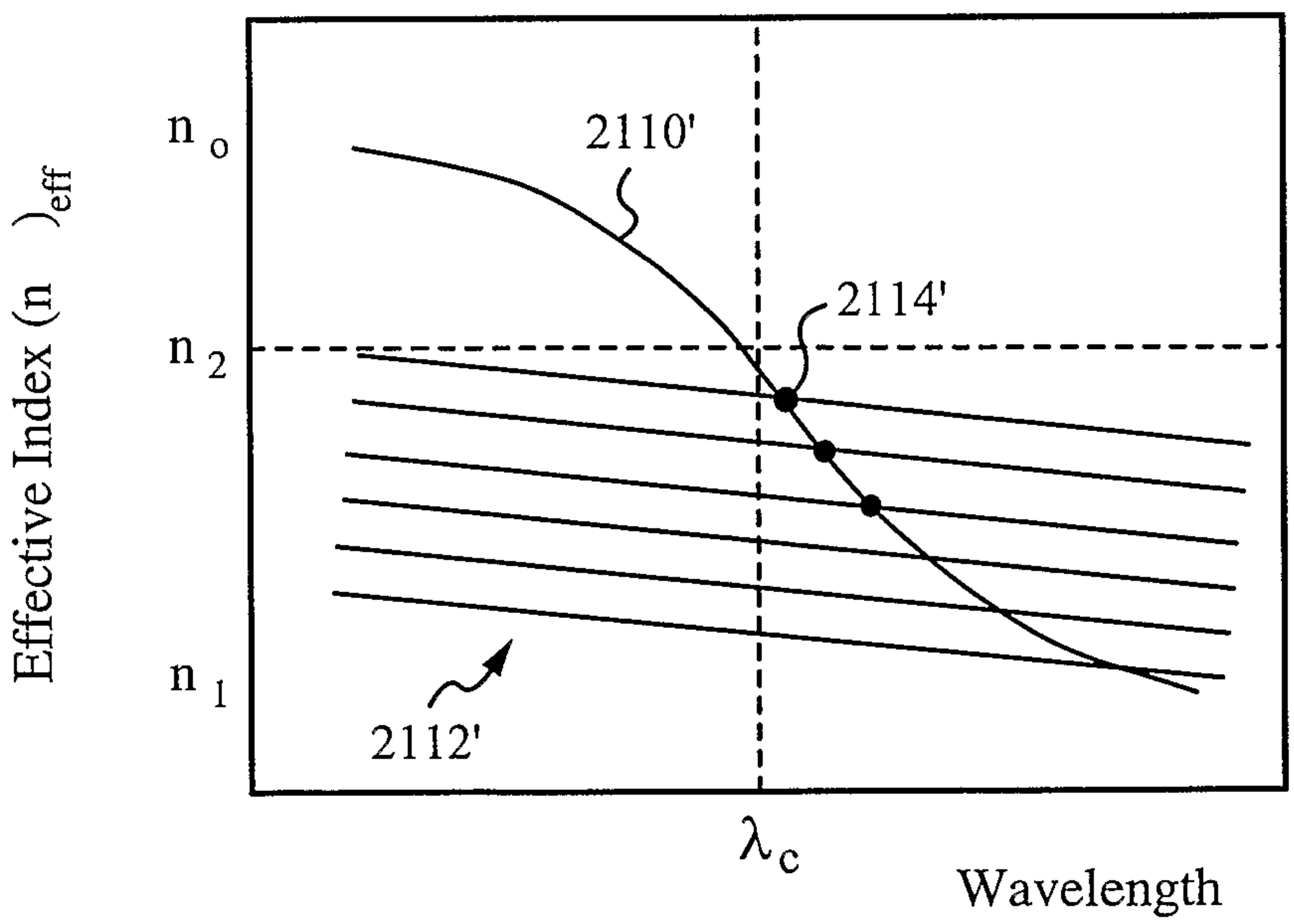


FIG. 20B

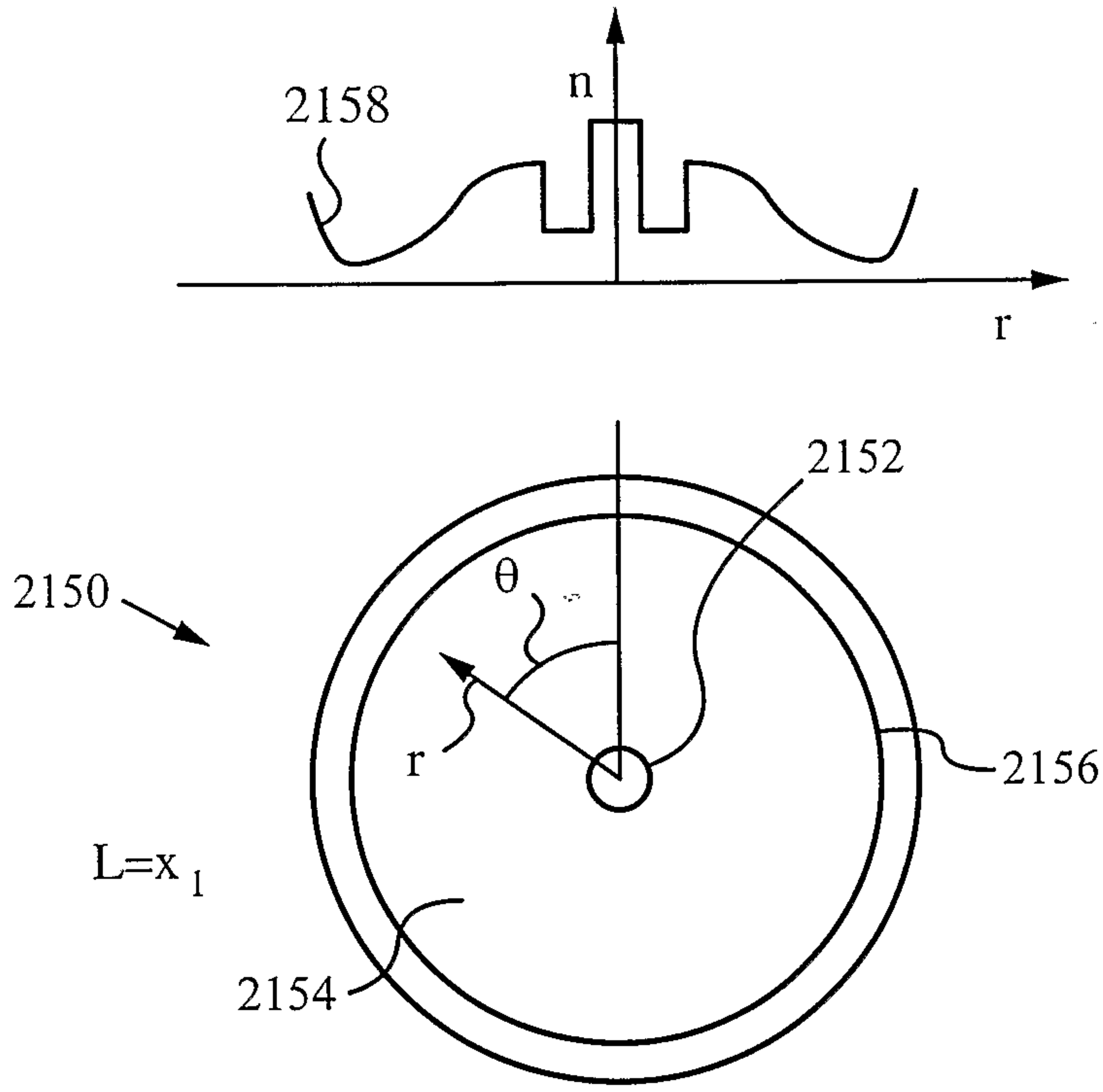


FIG. 21A

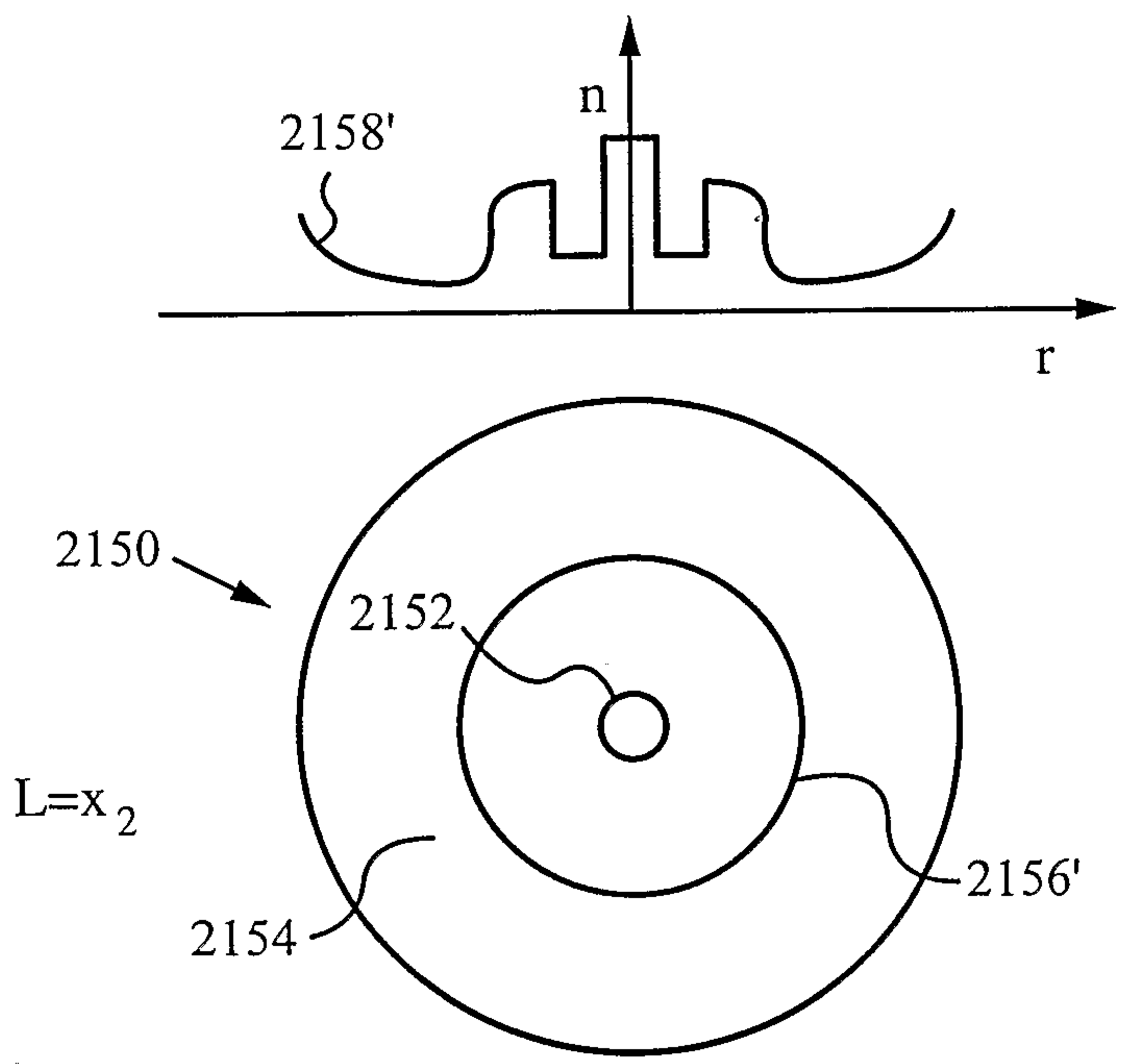


FIG. 21B

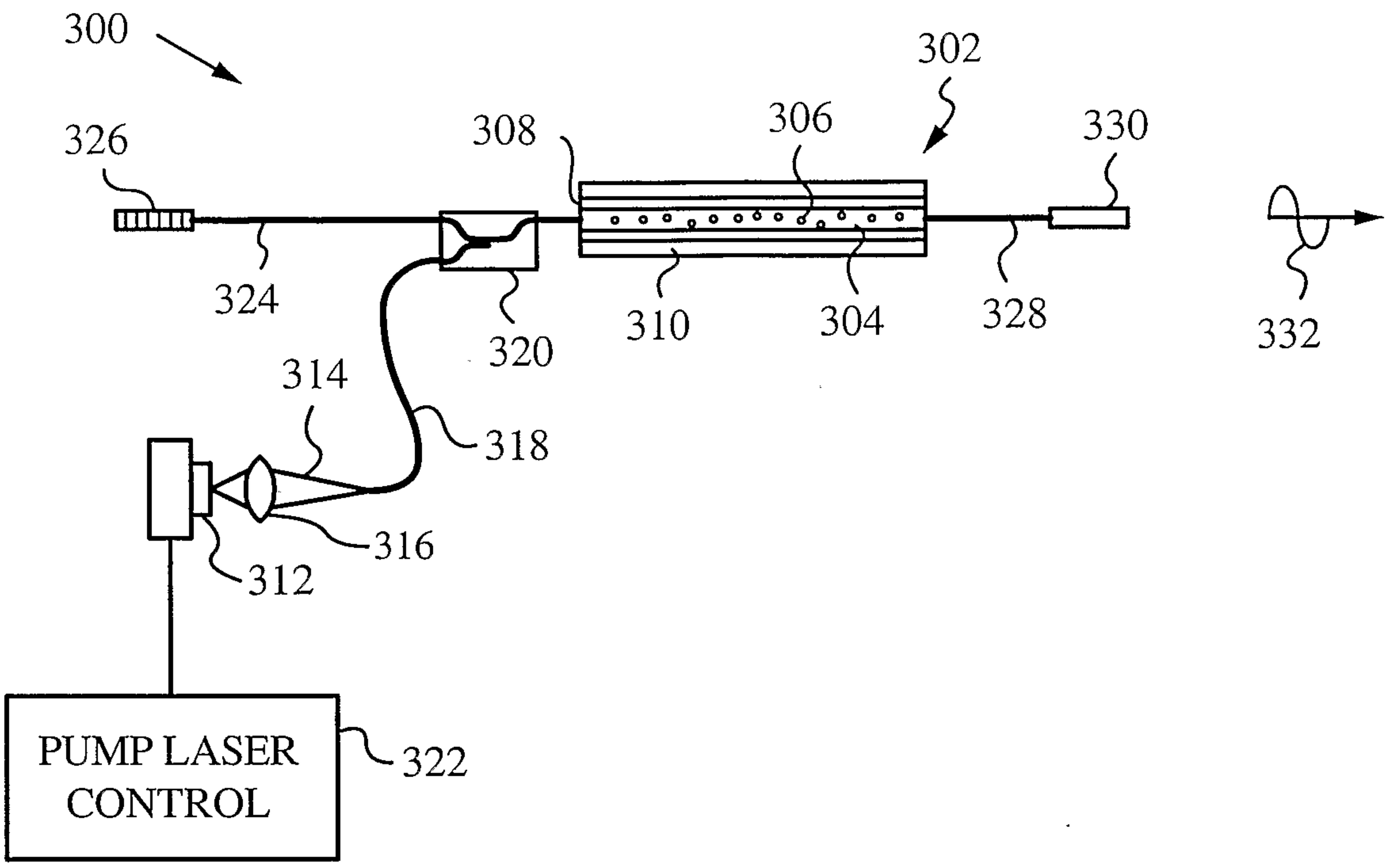

300
326
308
306
302
330
324
320
310
304
328
332
314
318
316
312
PUMP LASER CONTROL
322

FIG. 22

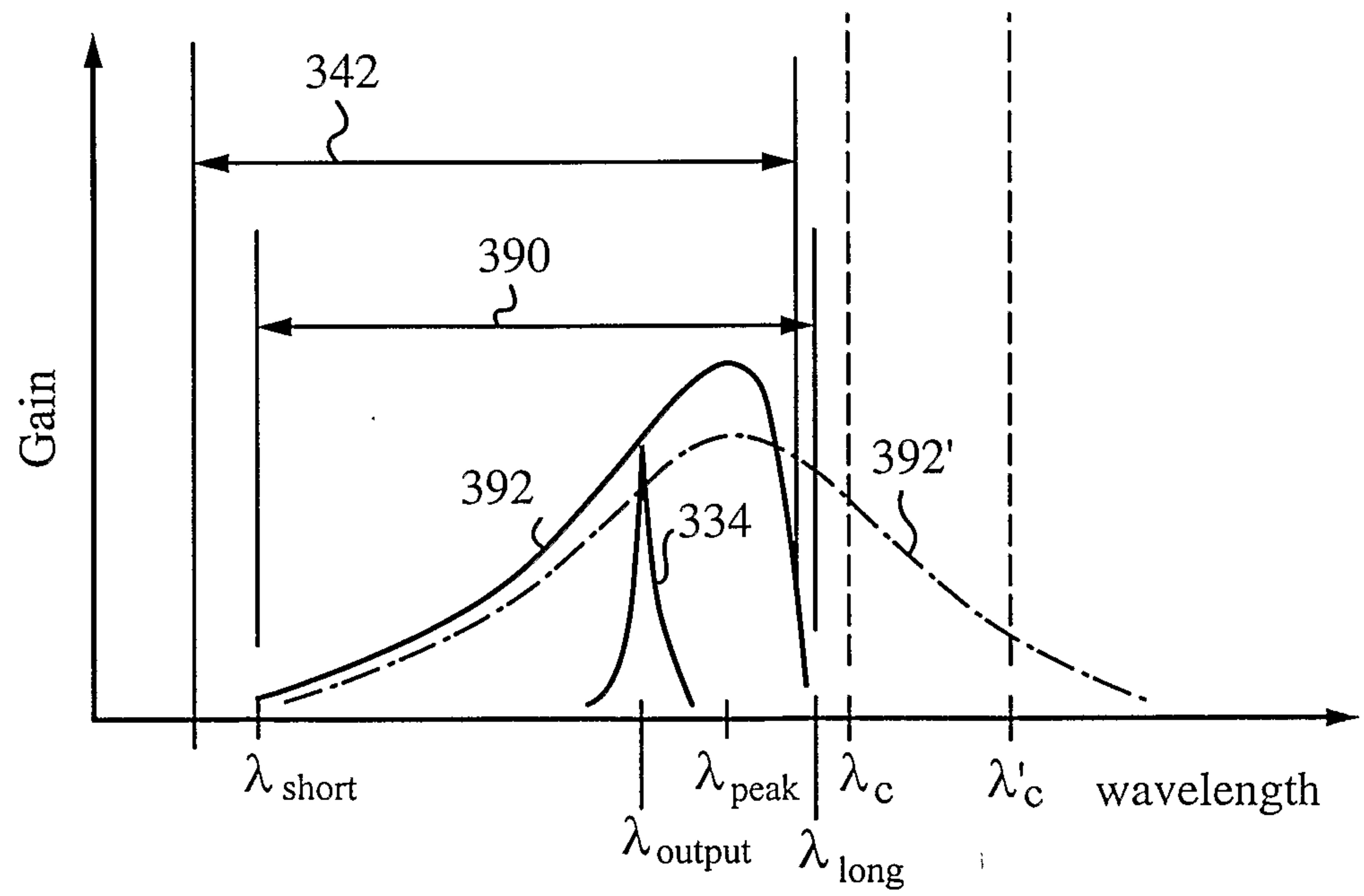

342
390
Gain
392
334
392'
λ short
λ output
λ peak
λ long
λ c
λ'c
wavelength

FIG. 23

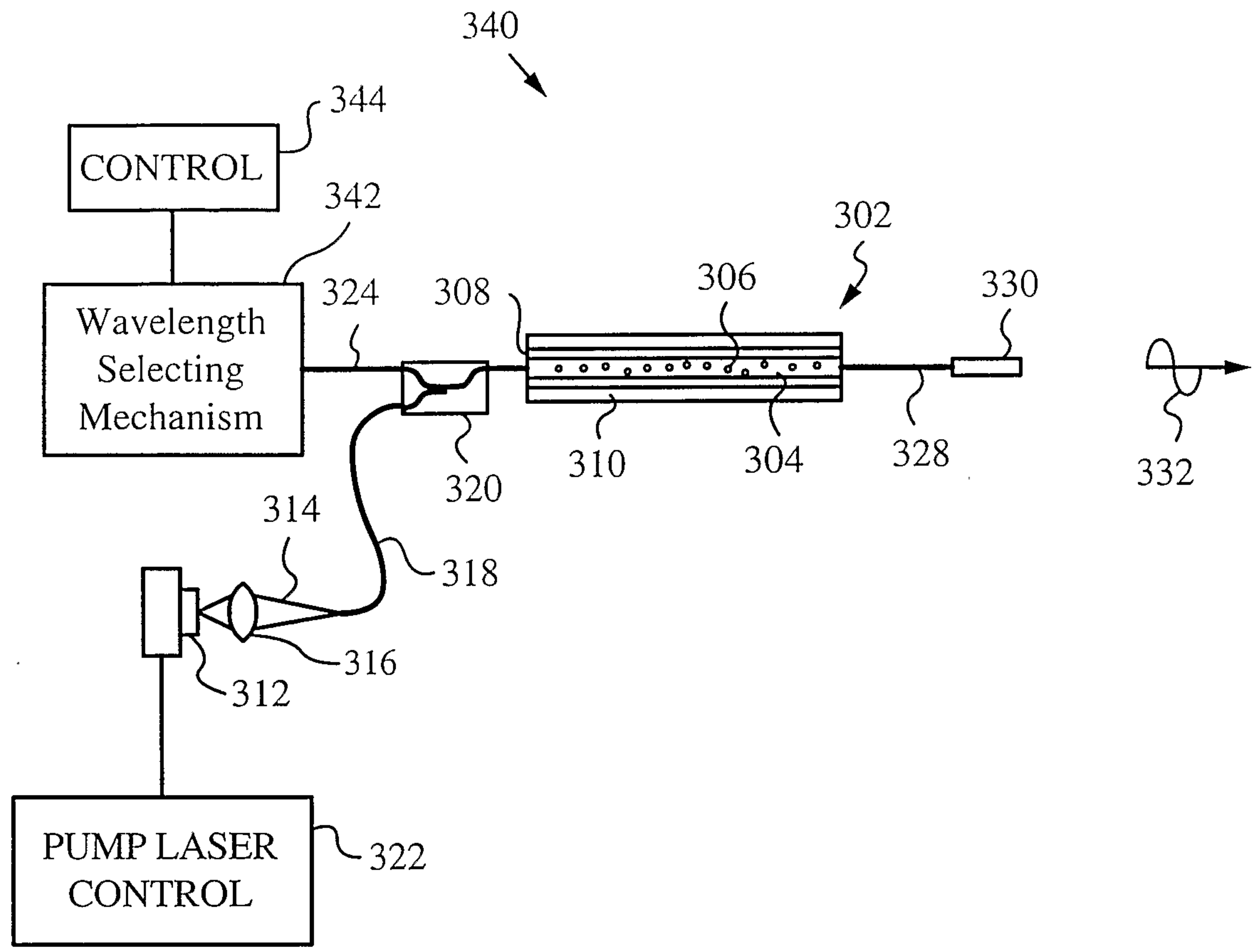

340
344
CONTROL
342
302
Wavelength Selecting Mechanism
324
308
306
330
310
304
328
332
320
314
318
316
312
PUMP LASER CONTROL
322

FIG. 24

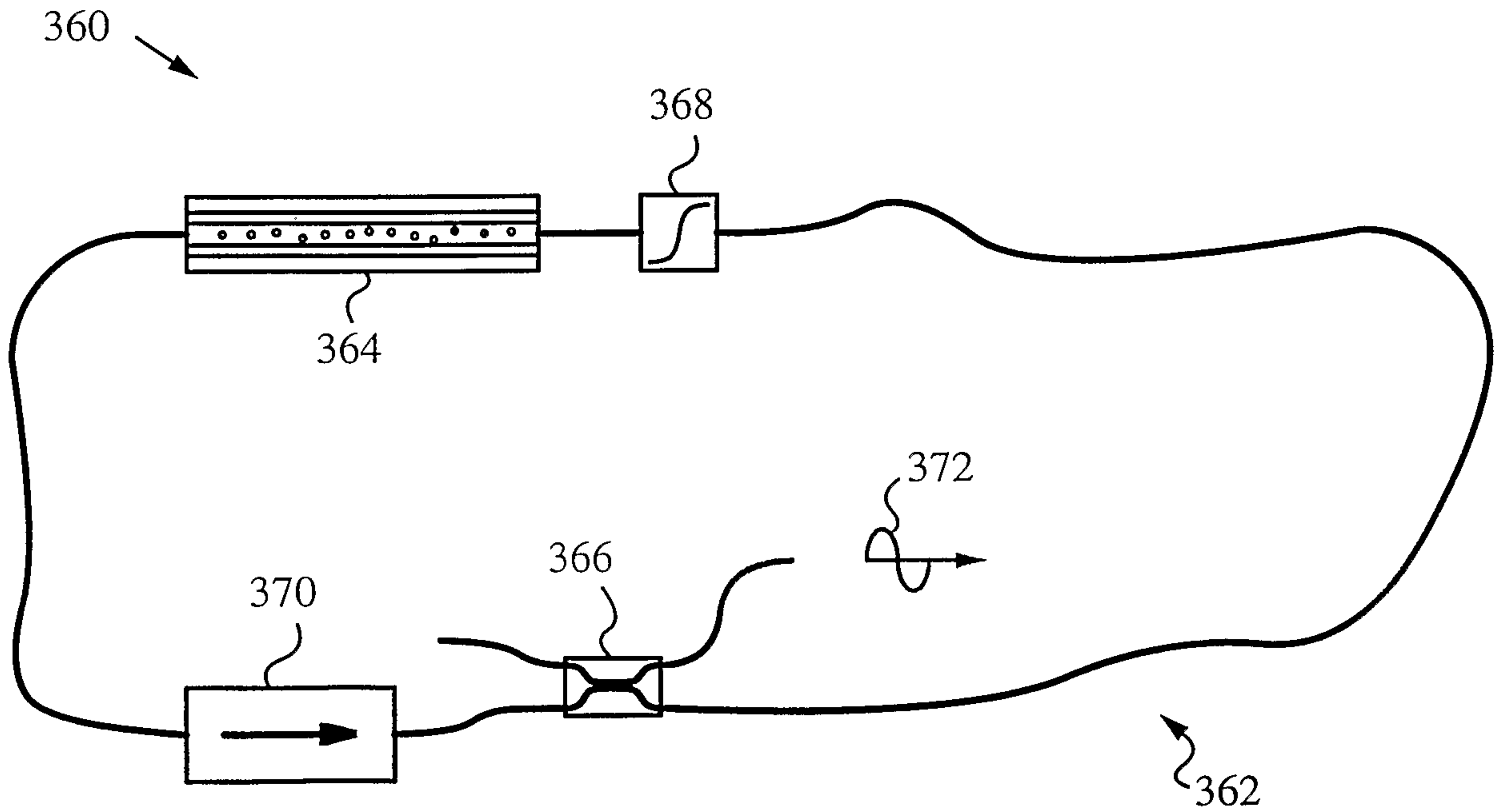

360
368
364
372
366
370
362

FIG. 25

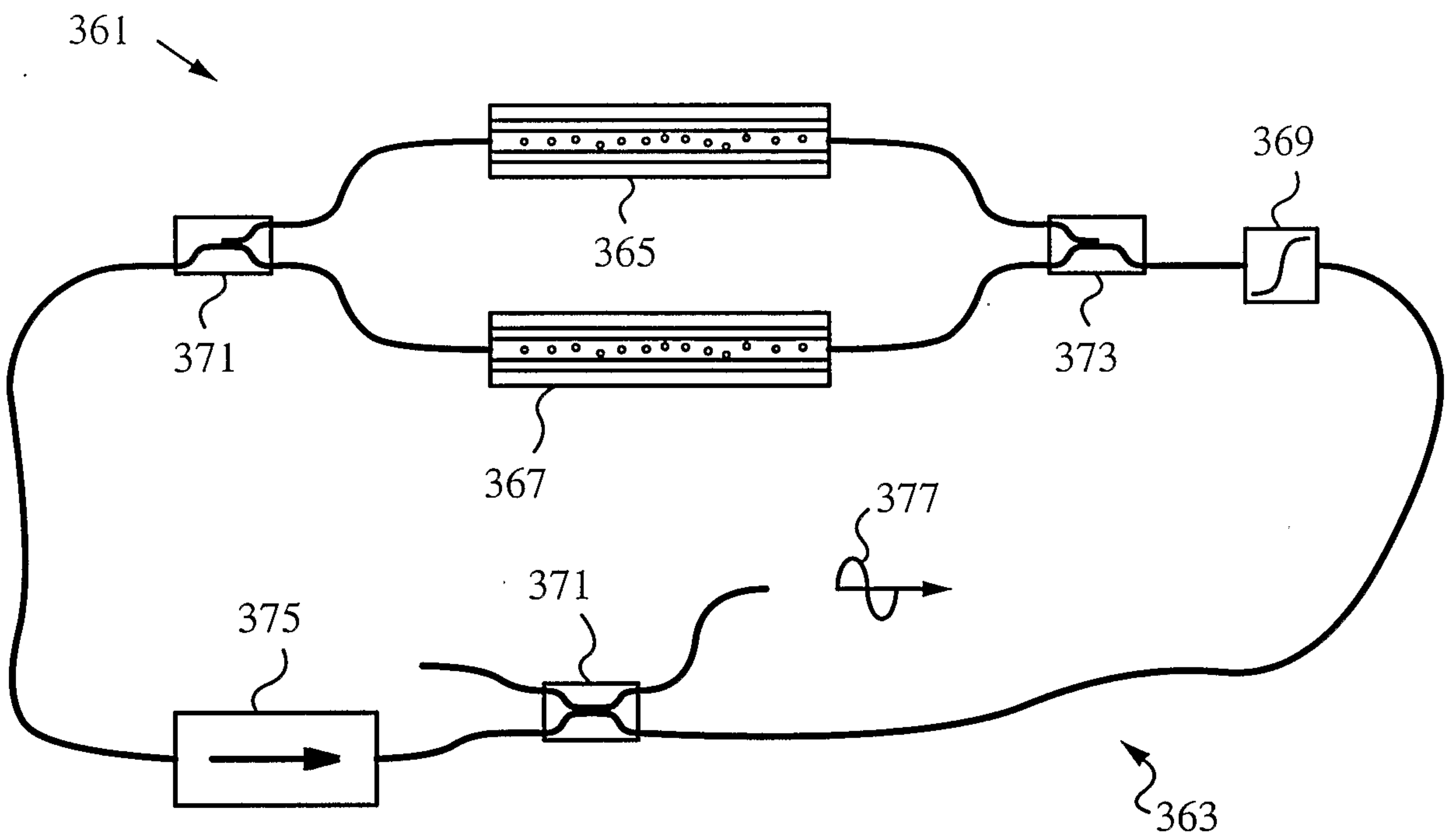

361
365
369
371
373
367
377
371
375
363

FIG. 26

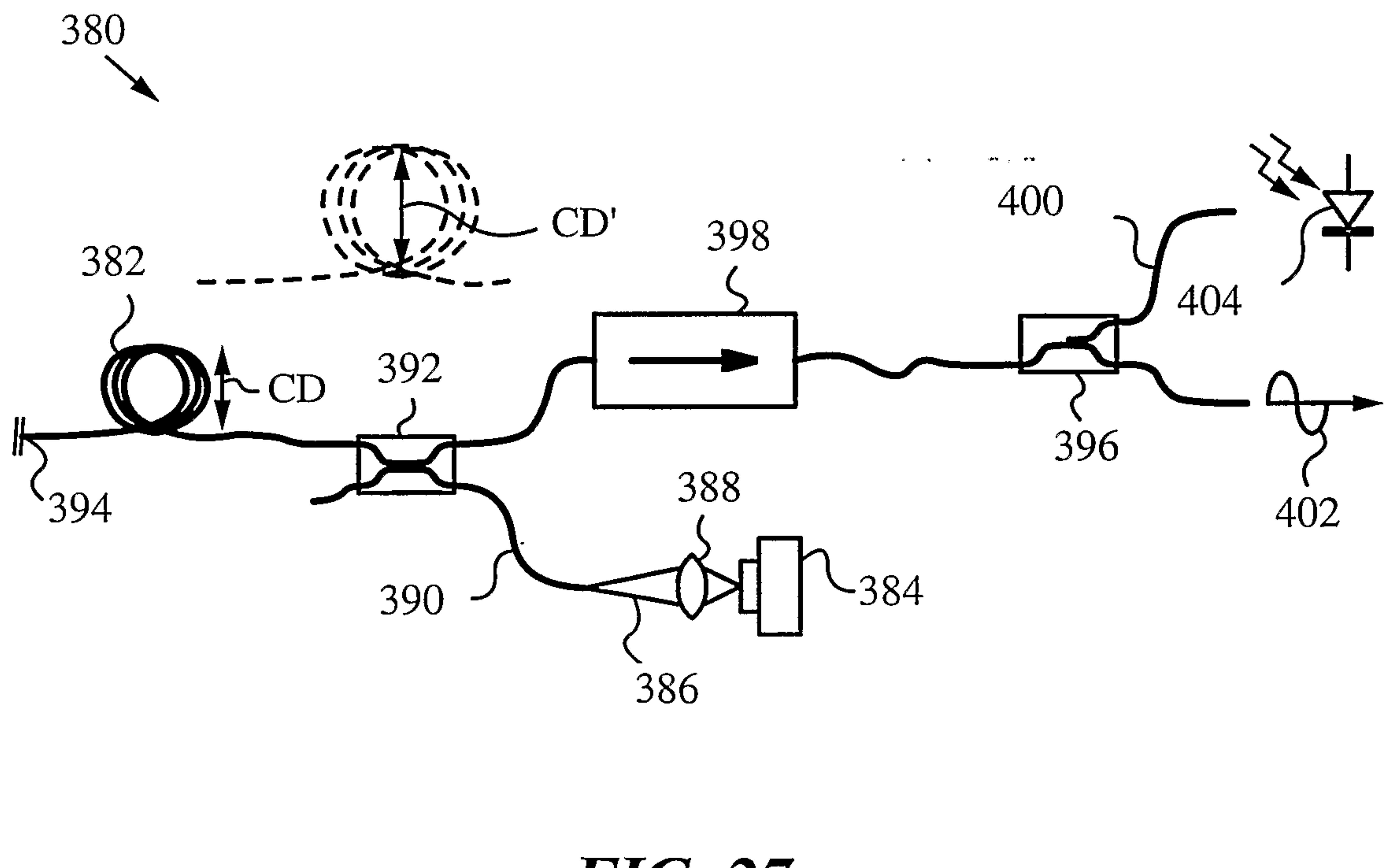

380
CD'
398
400
382
404
CD
392
396
394
402
388
390
384
386

FIG. 27

18/24

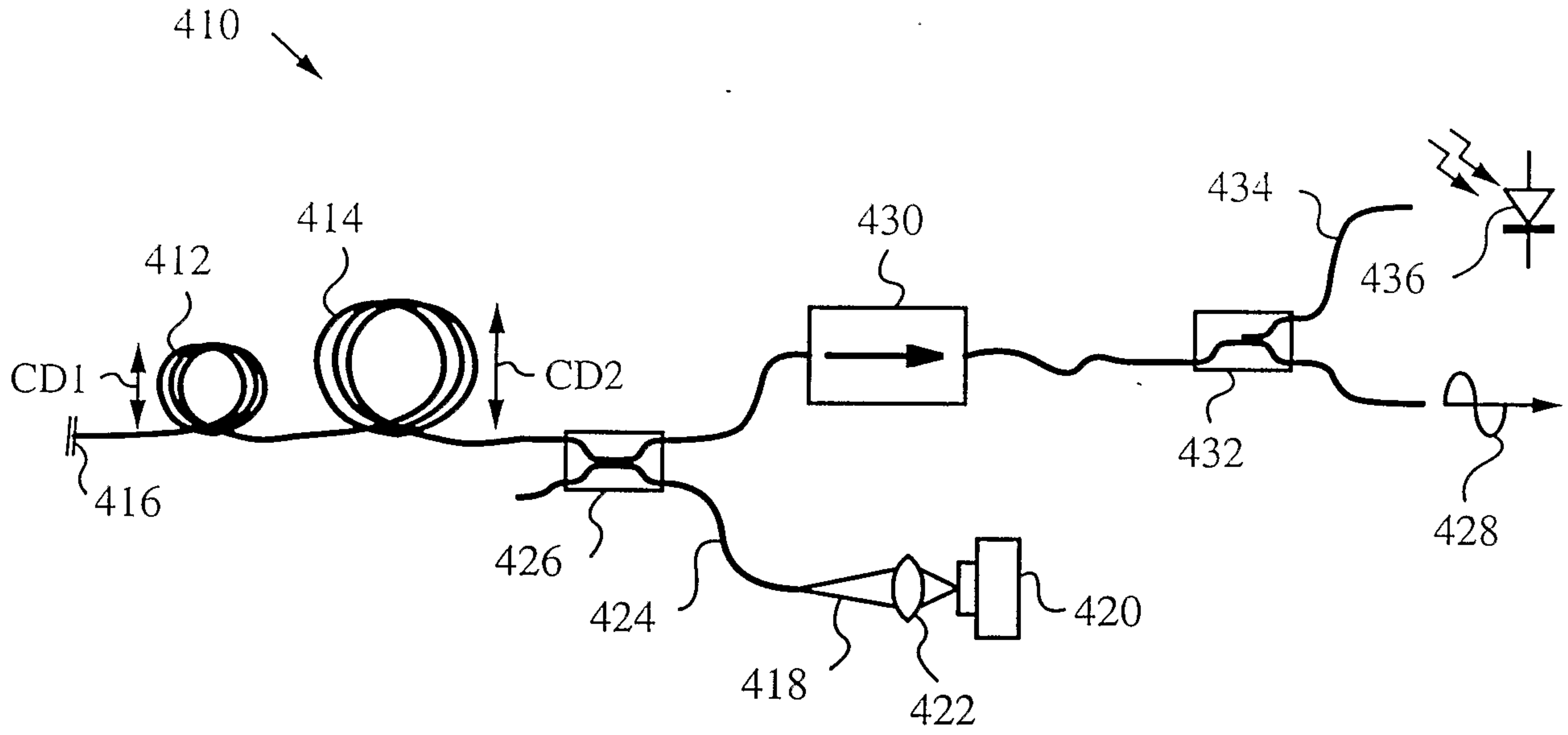


FIG. 28

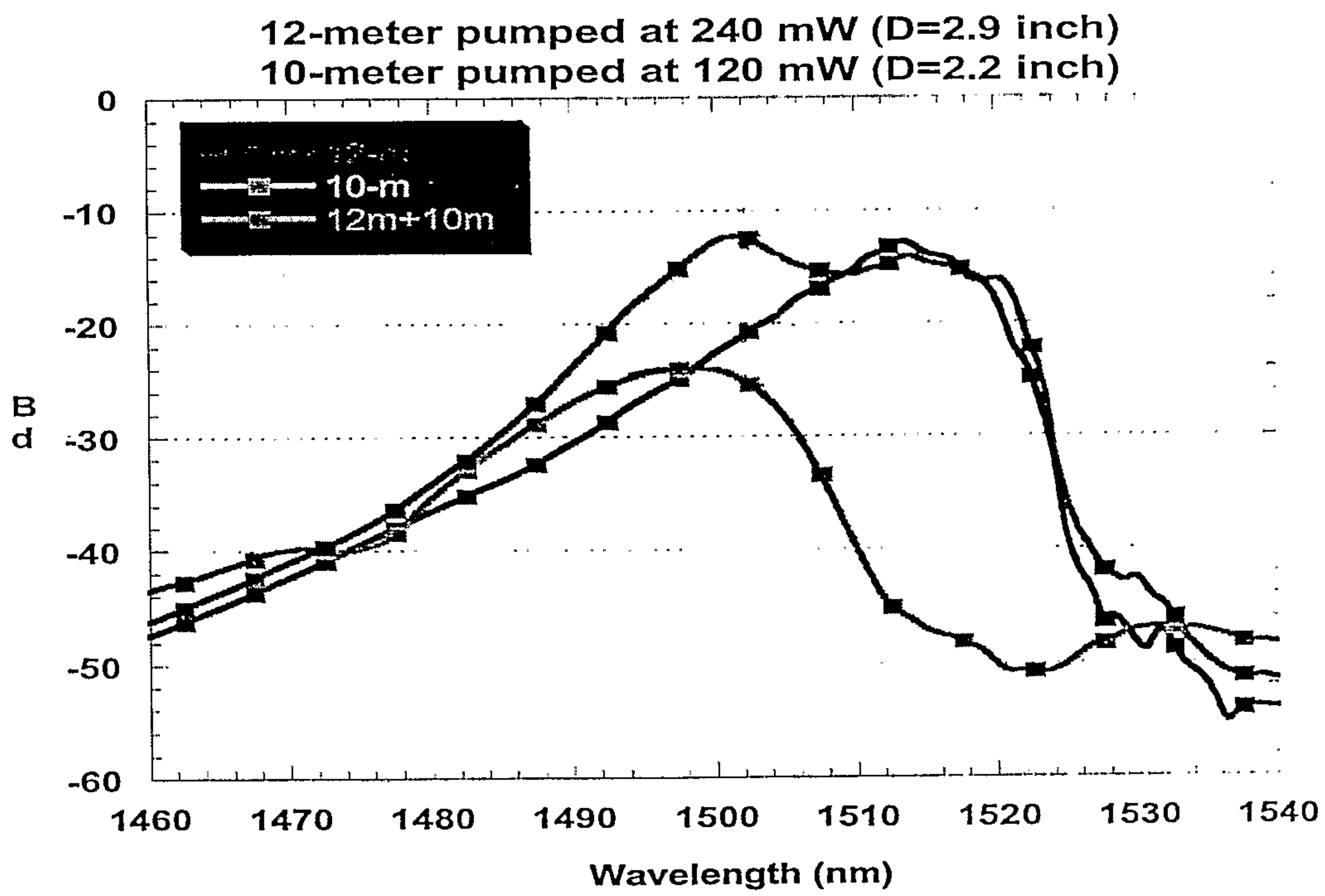


FIG. 29

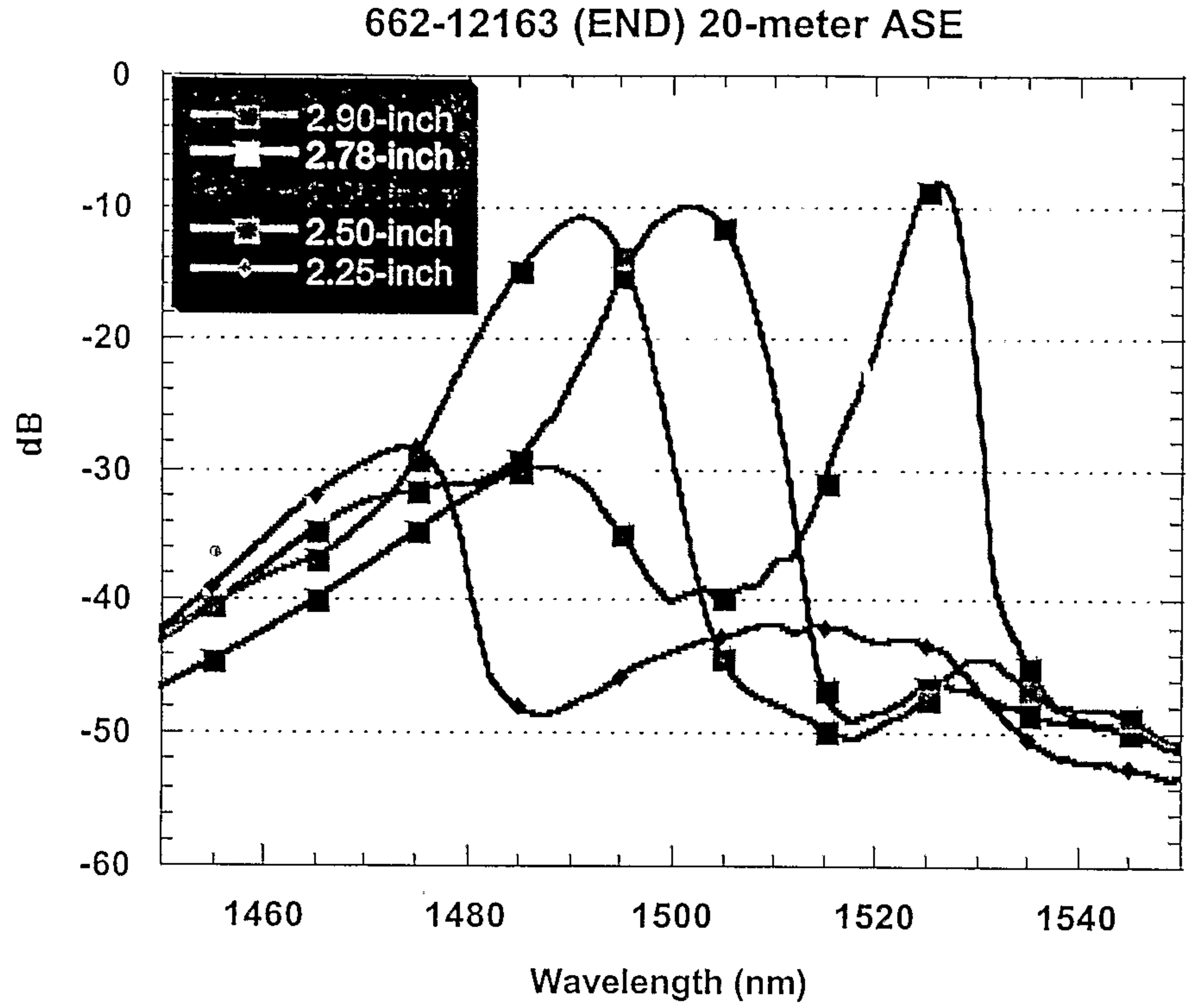

662-12163 (END) 20-meter ASE
2.90-inch
2.78-inch
2.50-inch
2.25-inch
dB
0
-10
-20
-30
-40
-50
-60
1460
1480
1500
1520
1540
Wavelength (nm)

FIG. 30

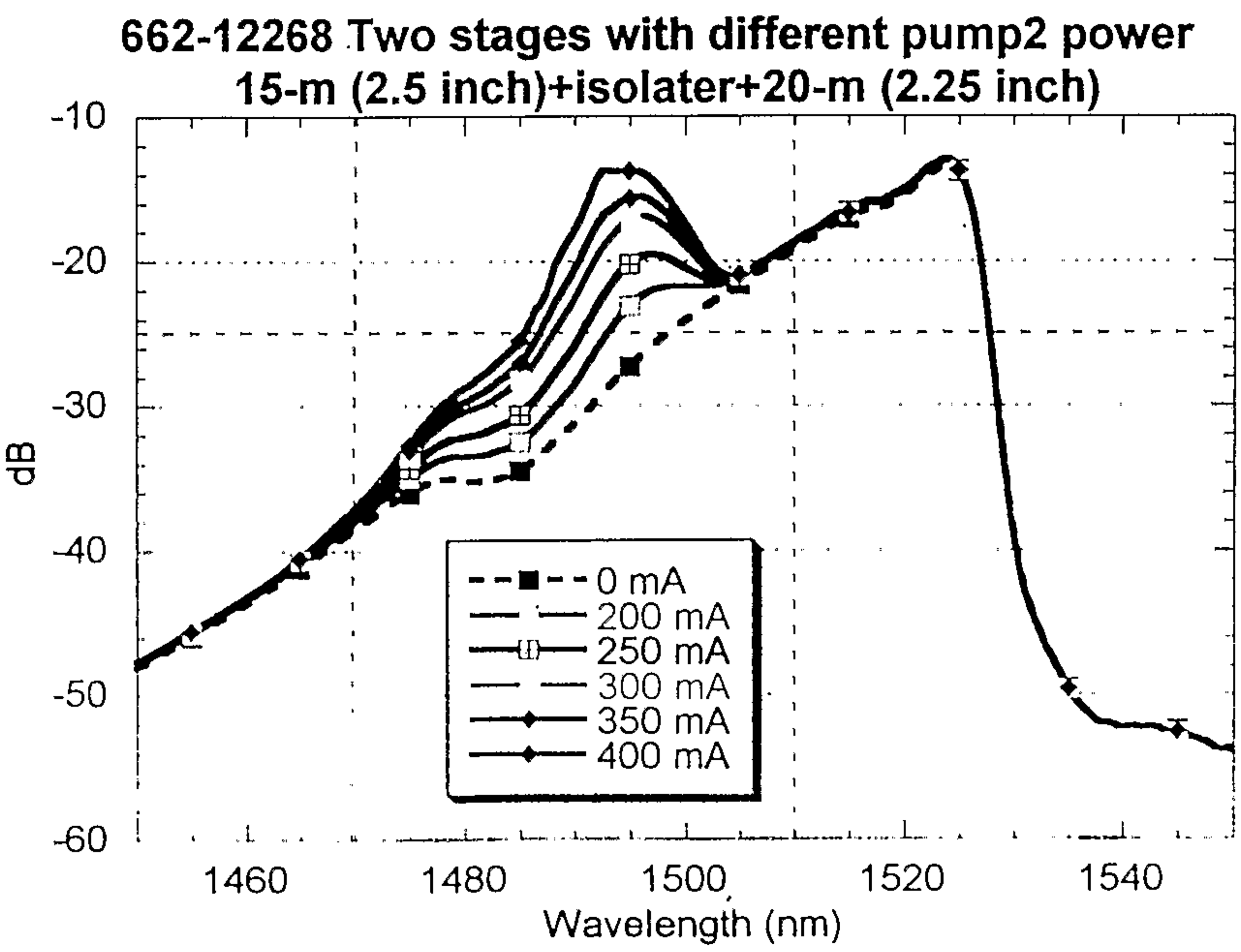

662-12268 Two stages with different pump2 power
15-m (2.5 inch)+isolater+20-m (2.25 inch)
dB
-10
-20
-30
-40
-50
-60
0 mA
200 mA
250 mA
300 mA
350 mA
400 mA
1460
1480
1500
1520
1540
Wavelength (nm)

FIG. 31

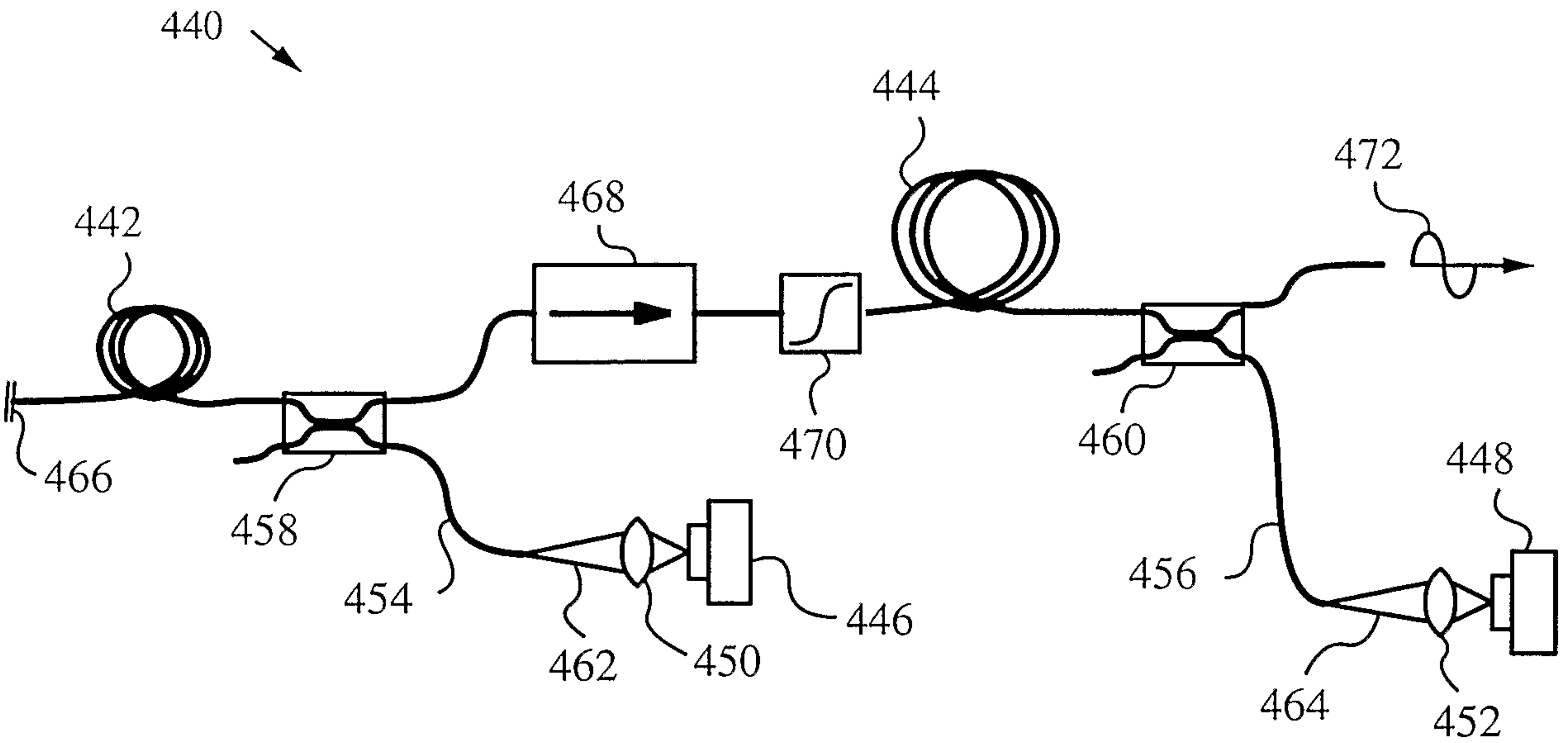

440
442
444
446
448
450
452
454
456
458
460
462
464
466
468
470
472

FIG. 32

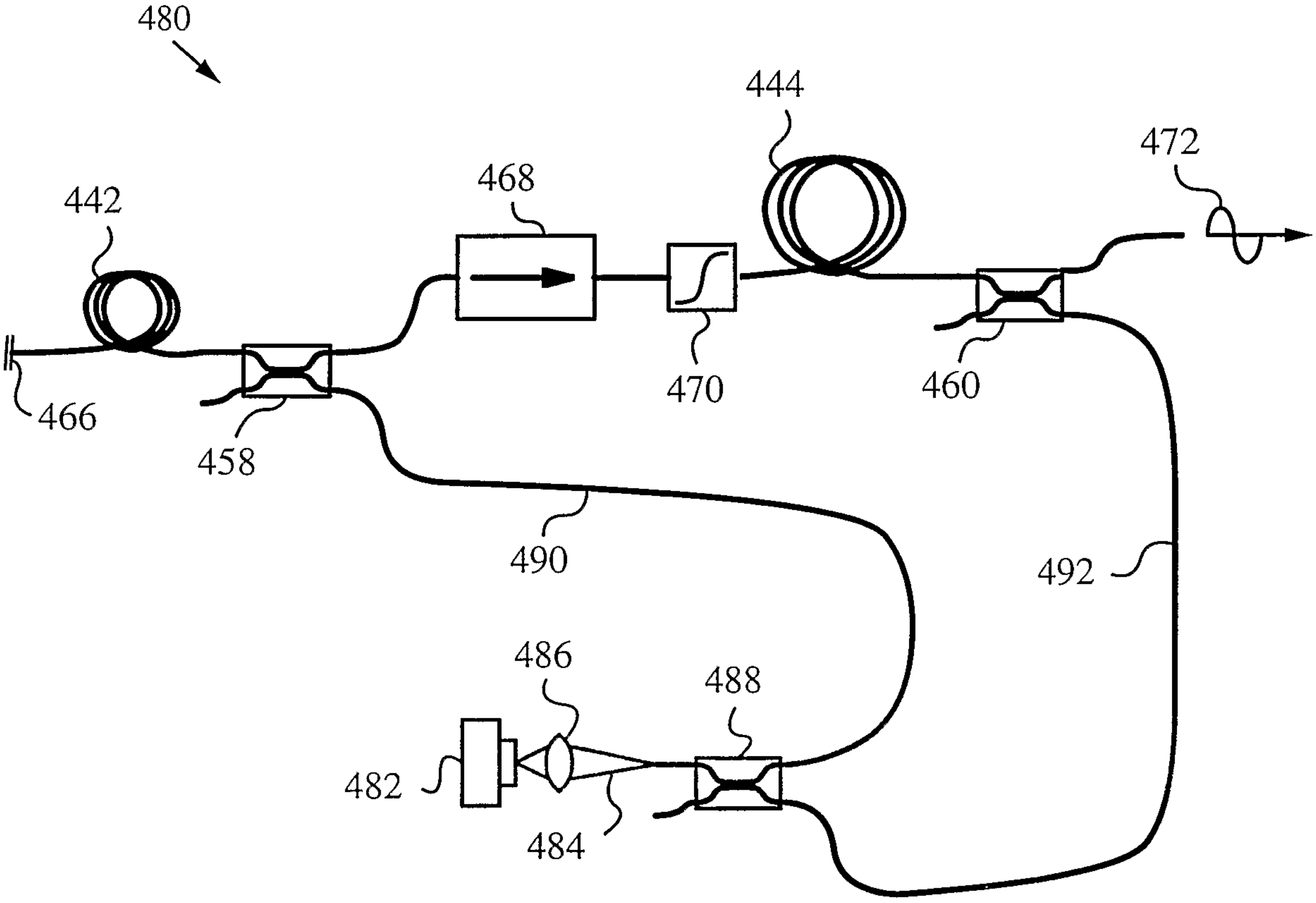

480
442
444
466
468
470
472
458
460
482
484
486
488
490
492

FIG. 33

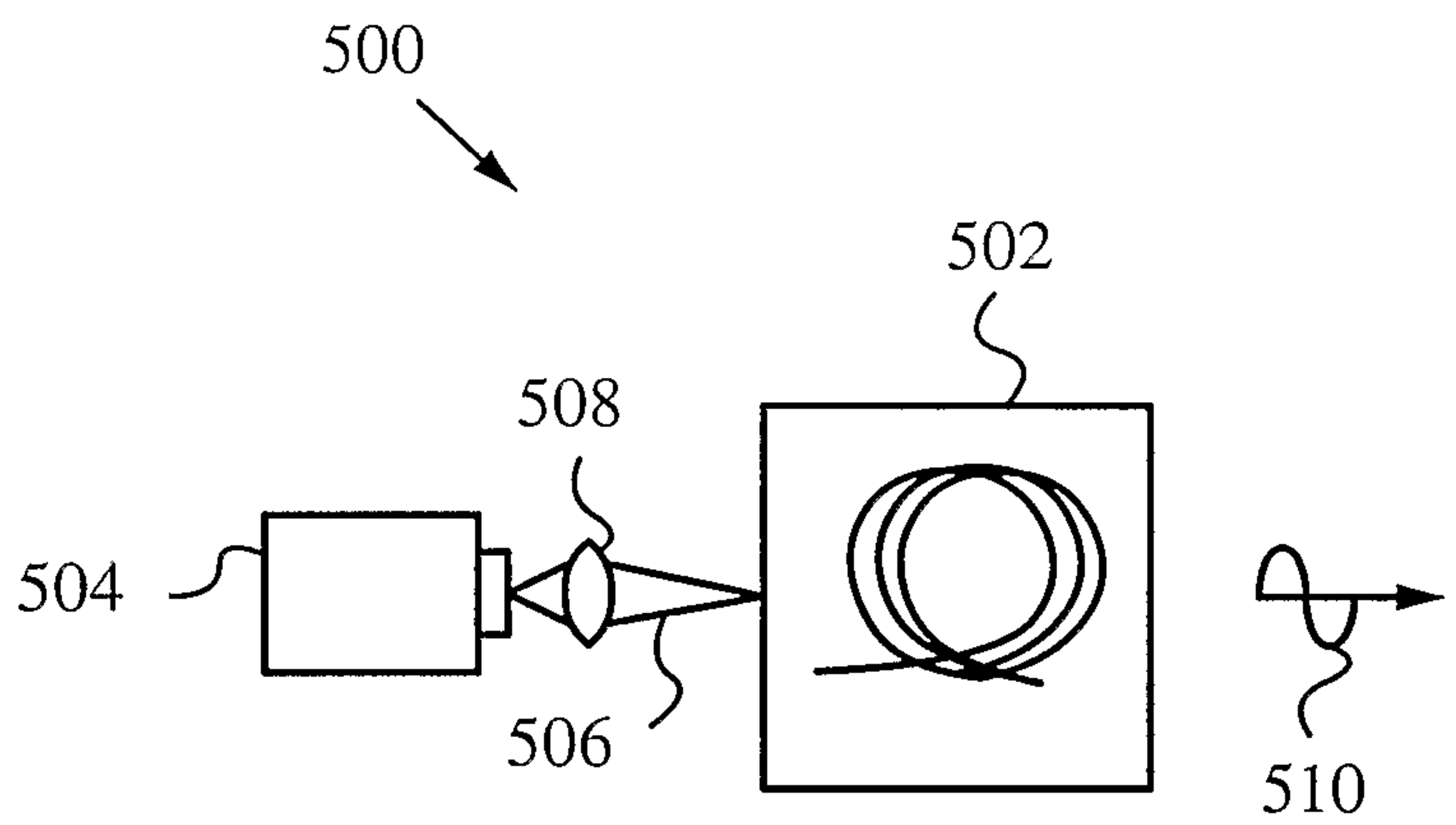


FIG. 34

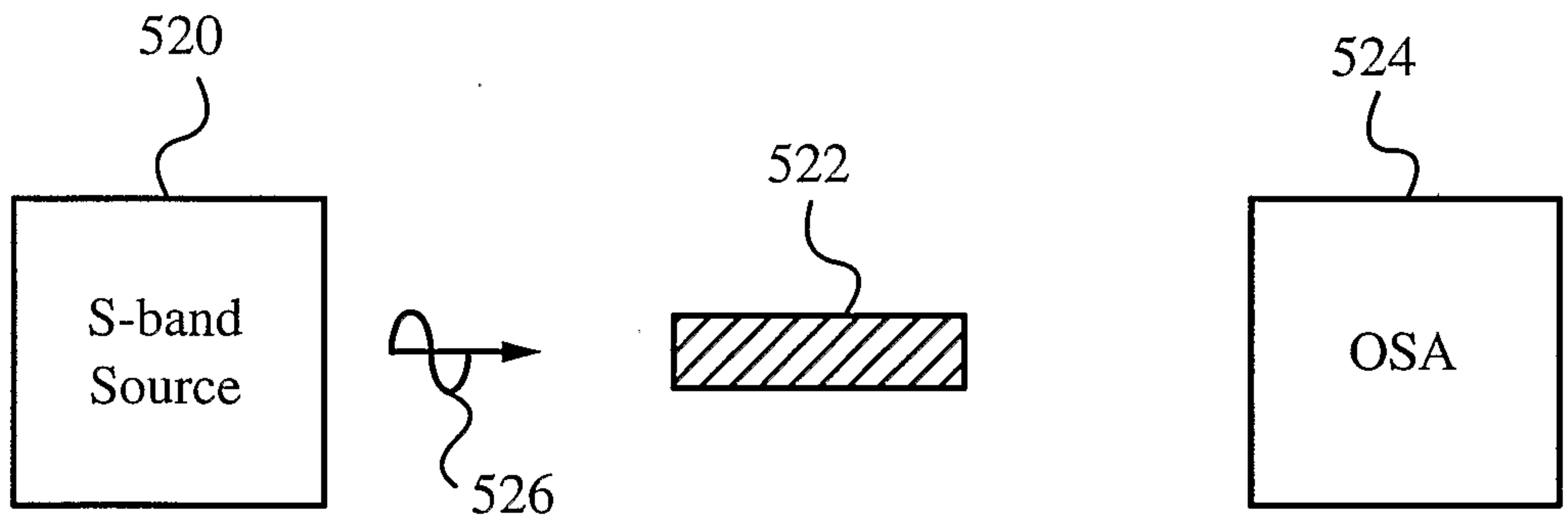


FIG. 35

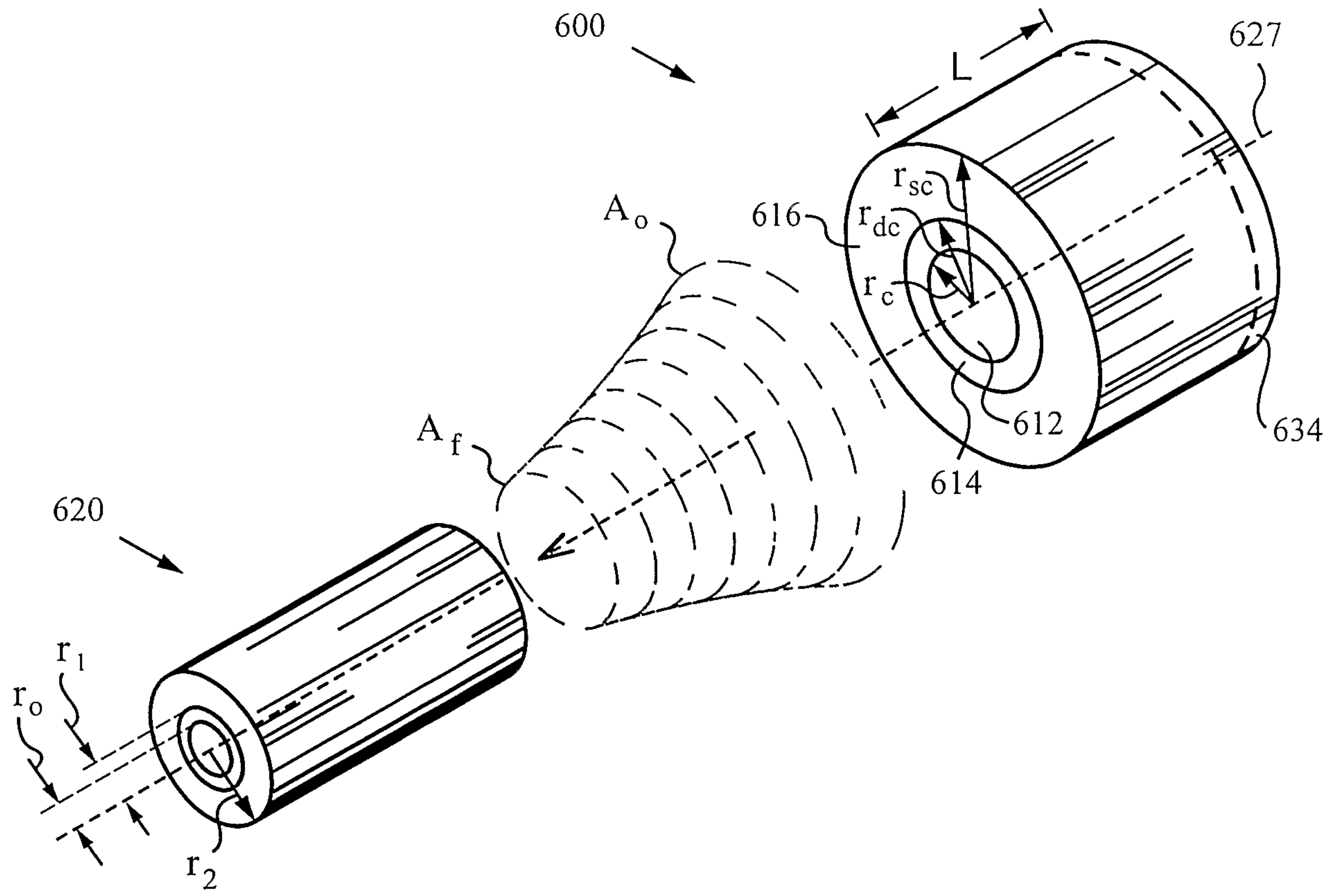


FIG. 36

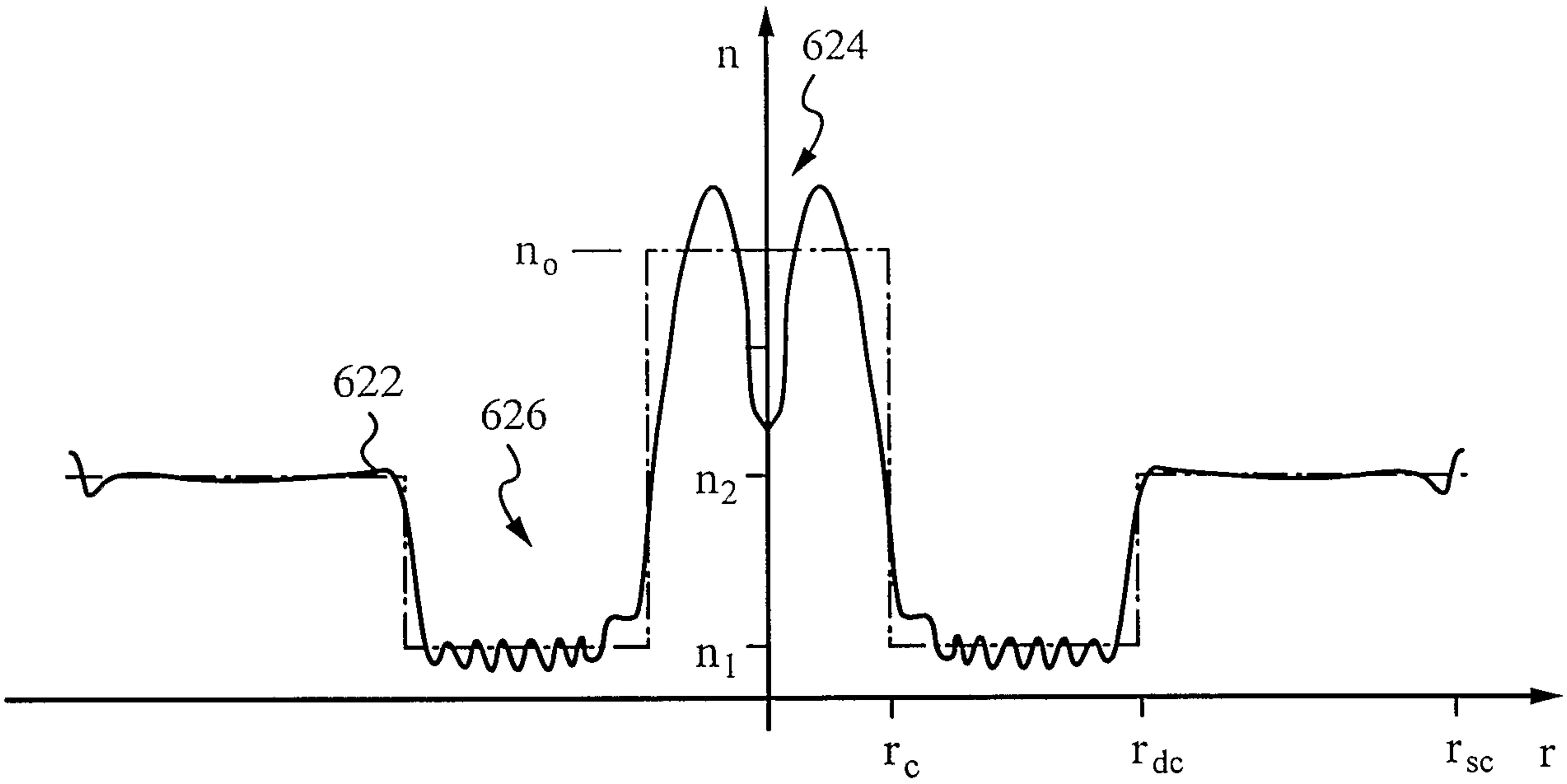


FIG. 37A

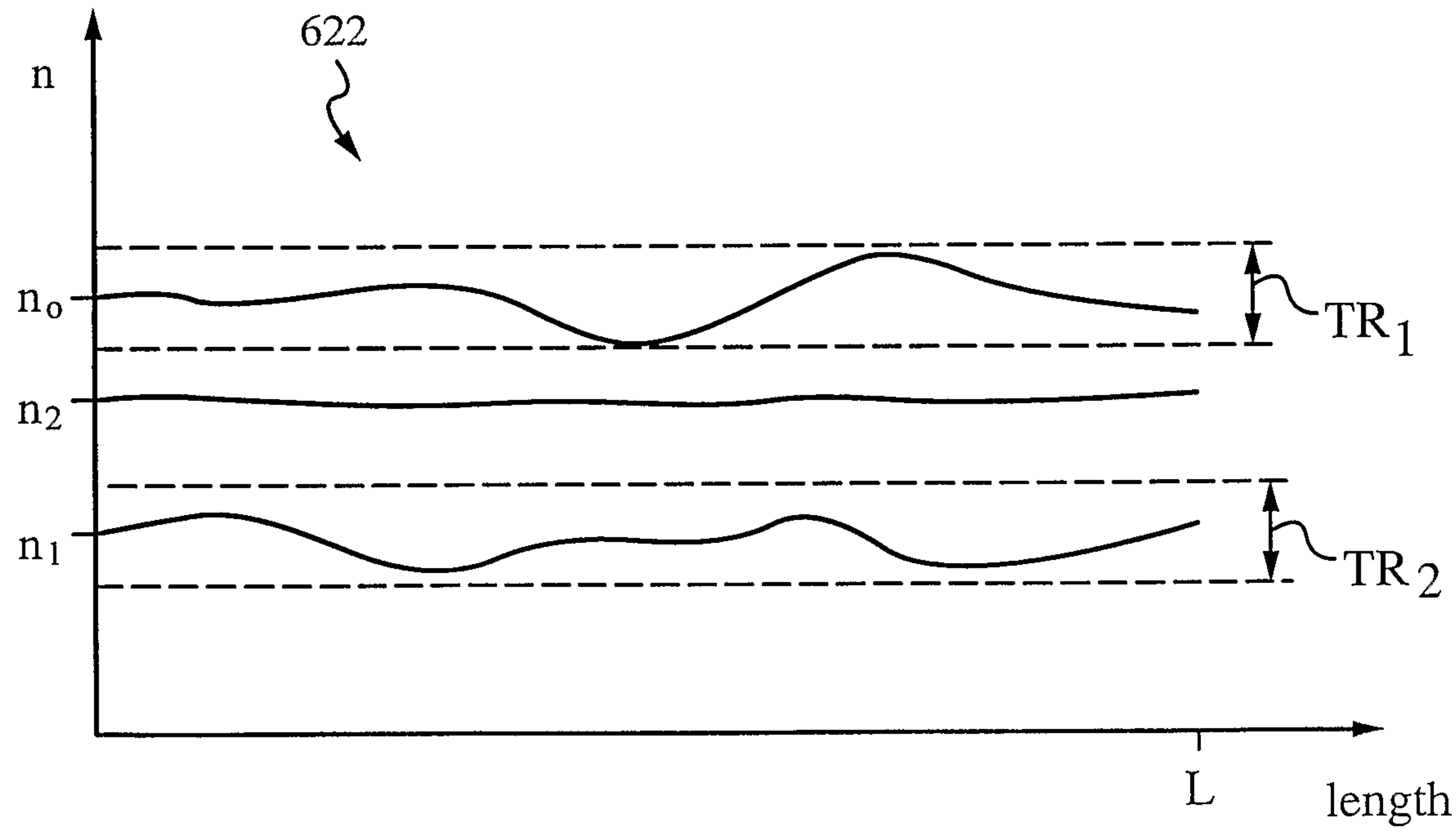


FIG. 37B

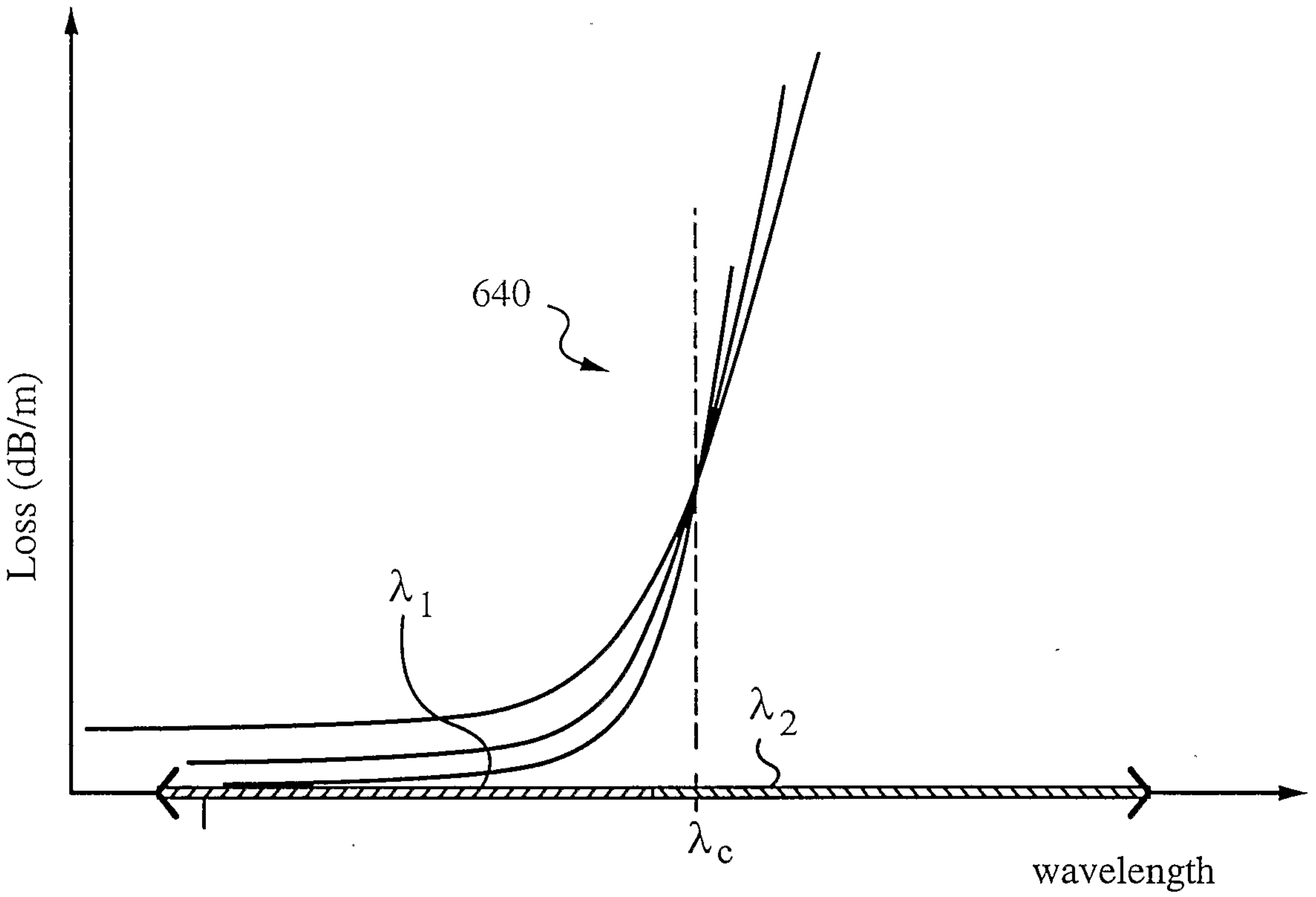

Loss (dB/m)
640
λ1
λ2
λc
wavelength

FIG. 38

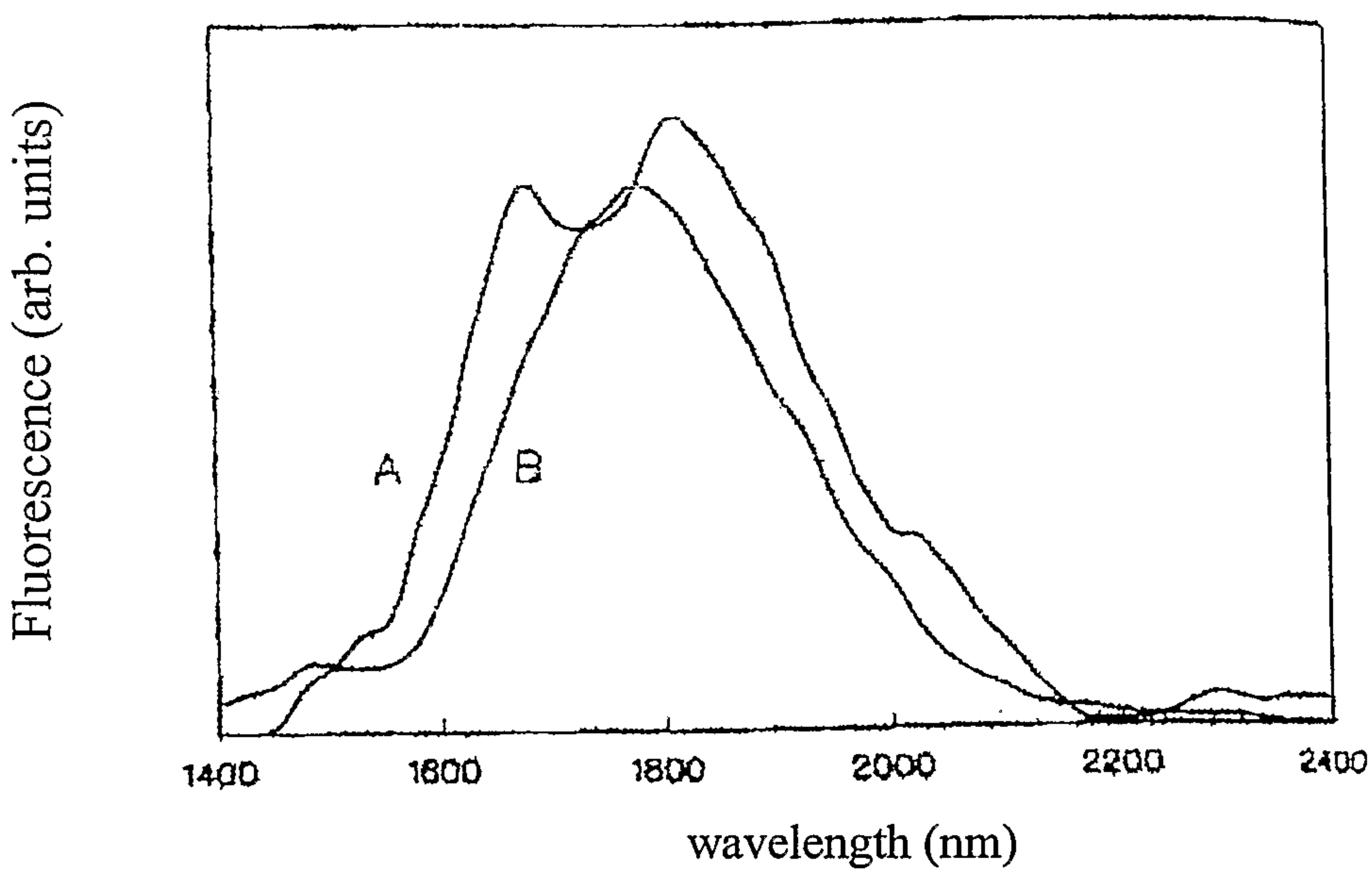
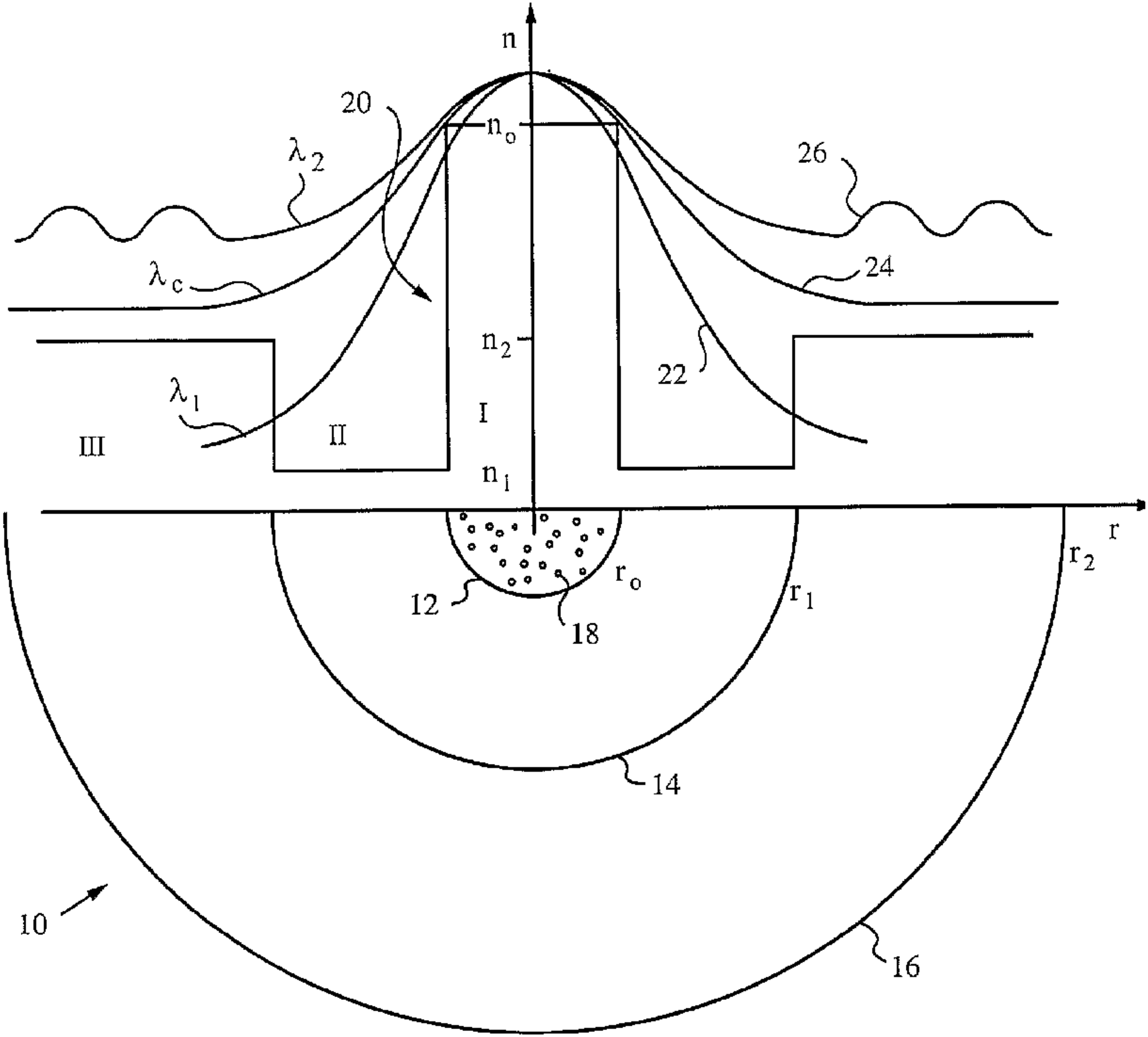

Fluorescence (arb. units)
A
B
1400
1600
1800
2000
2200
2400
wavelength (nm)

FIG. 39



n
20
n_o
λ_2
26
λ_c
24
n_2
22
λ_1
I
II
III
n_1
r
r_2
r_o
r_1
12
18
14
10
16