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(54) **TWO-STAGE GAIN EQUALIZER**

(75) Inventors: **Robert W. Corrigan**, Sisters, OR (US); **Dinesh Maheshwari**, Fremont, CA (US)

(73) Assignee: **Silicon Light Machines Corporation**, San Jose, CA (US)

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(58) **Field of Classification Search** 398/50, 398/188–189, 93–94, 78–79
See application file for complete search history.

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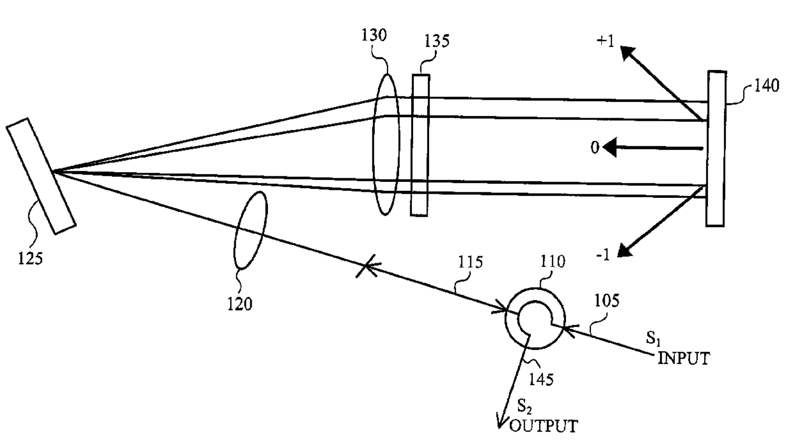
Primary Examiner—Jason Chan
Assistant Examiner—Wai Lun Leung
(74) *Attorney, Agent, or Firm*—Okamoto & Benedicto LLP

(57) **ABSTRACT**

An apparatus for selectively adjusting power levels of component signals of a wavelength division multiplexed signal. The apparatus comprises a first filter and a second filter. The first filter modulates the component signals according to a static attenuation profile, thereby providing coarsely modulated component signals. The second filter is coupled to the first filter to receive the coarsely modulated component signals and to modulate the coarsely modulated component signals according to a dynamic attenuation profile, thereby providing finely modulated component signals.

10 Claims, 12 Drawing Sheets



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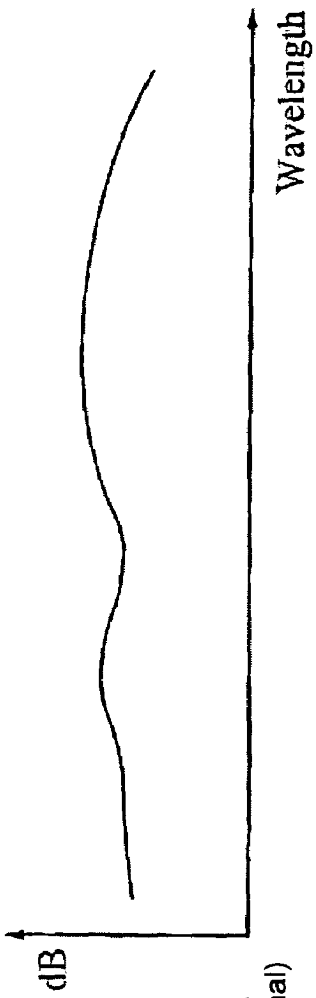

Fig. 1A
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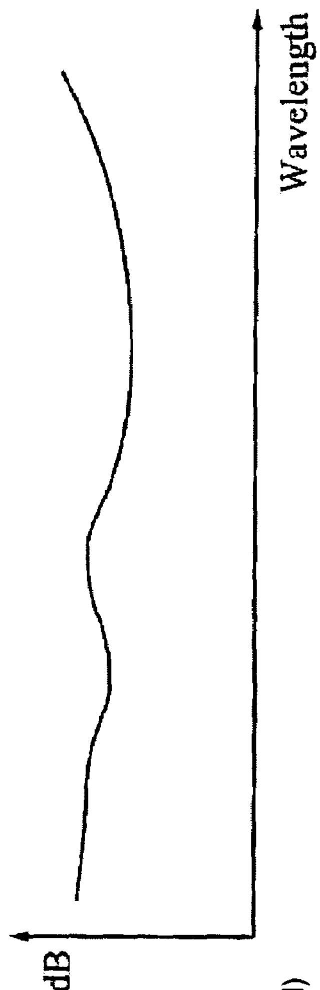

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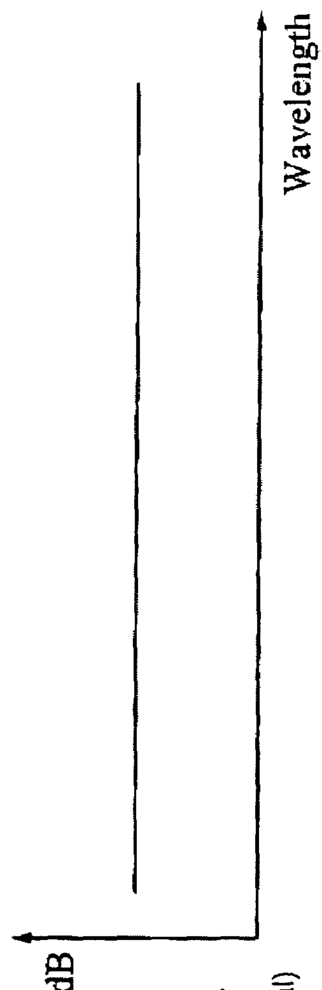

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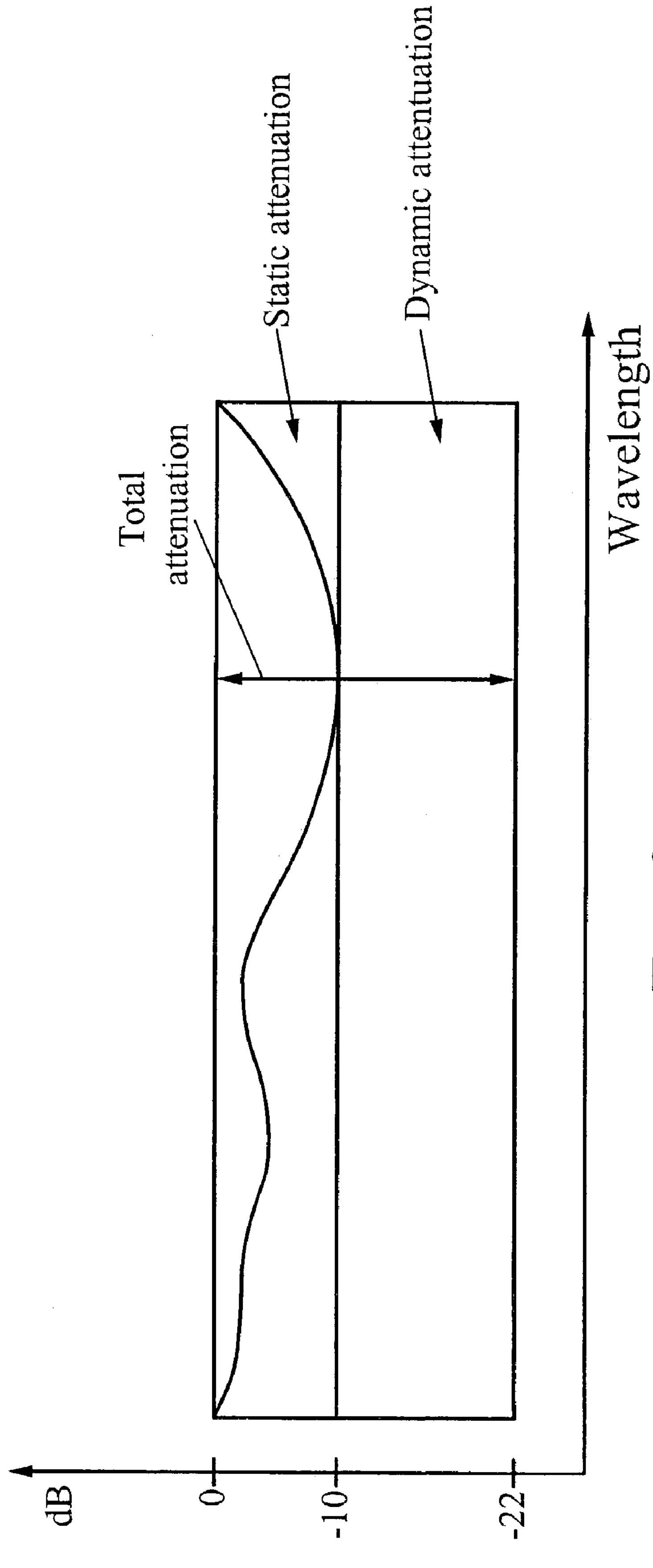
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Dynamic attenuation
Total attenuation
Wavelength
dB
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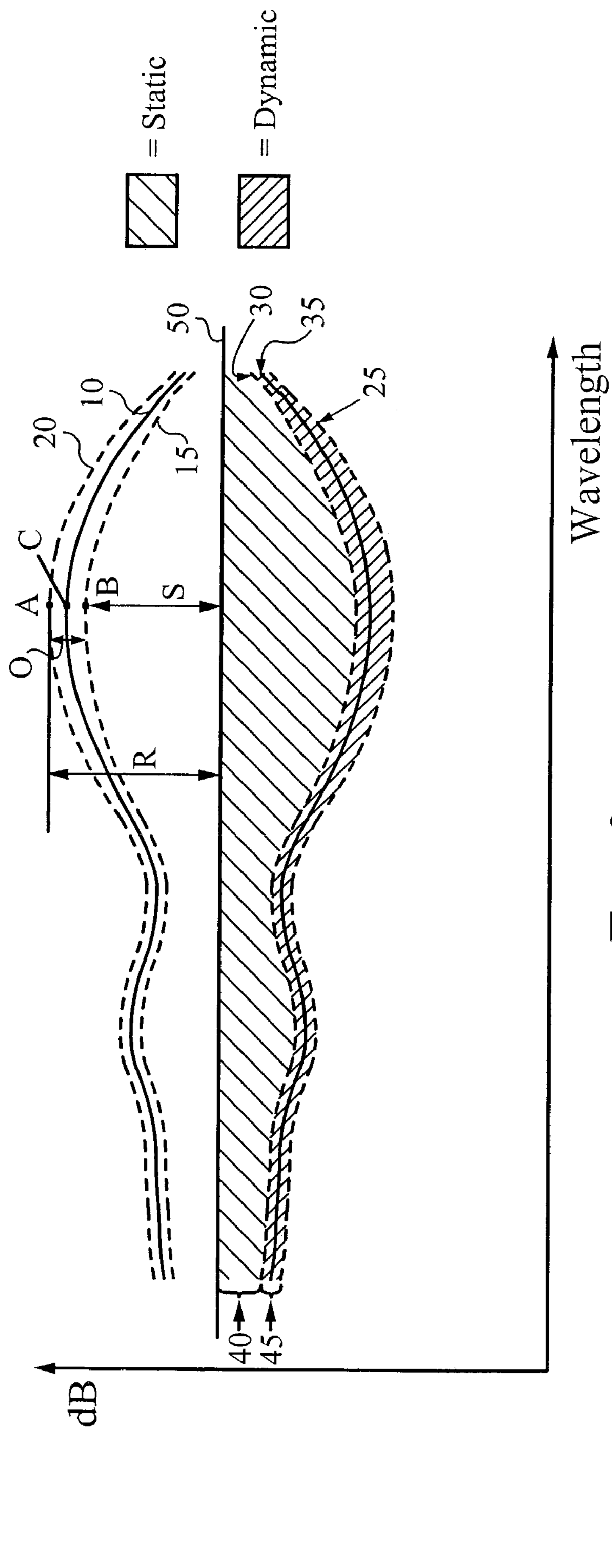
-10
-22

Fig. 2



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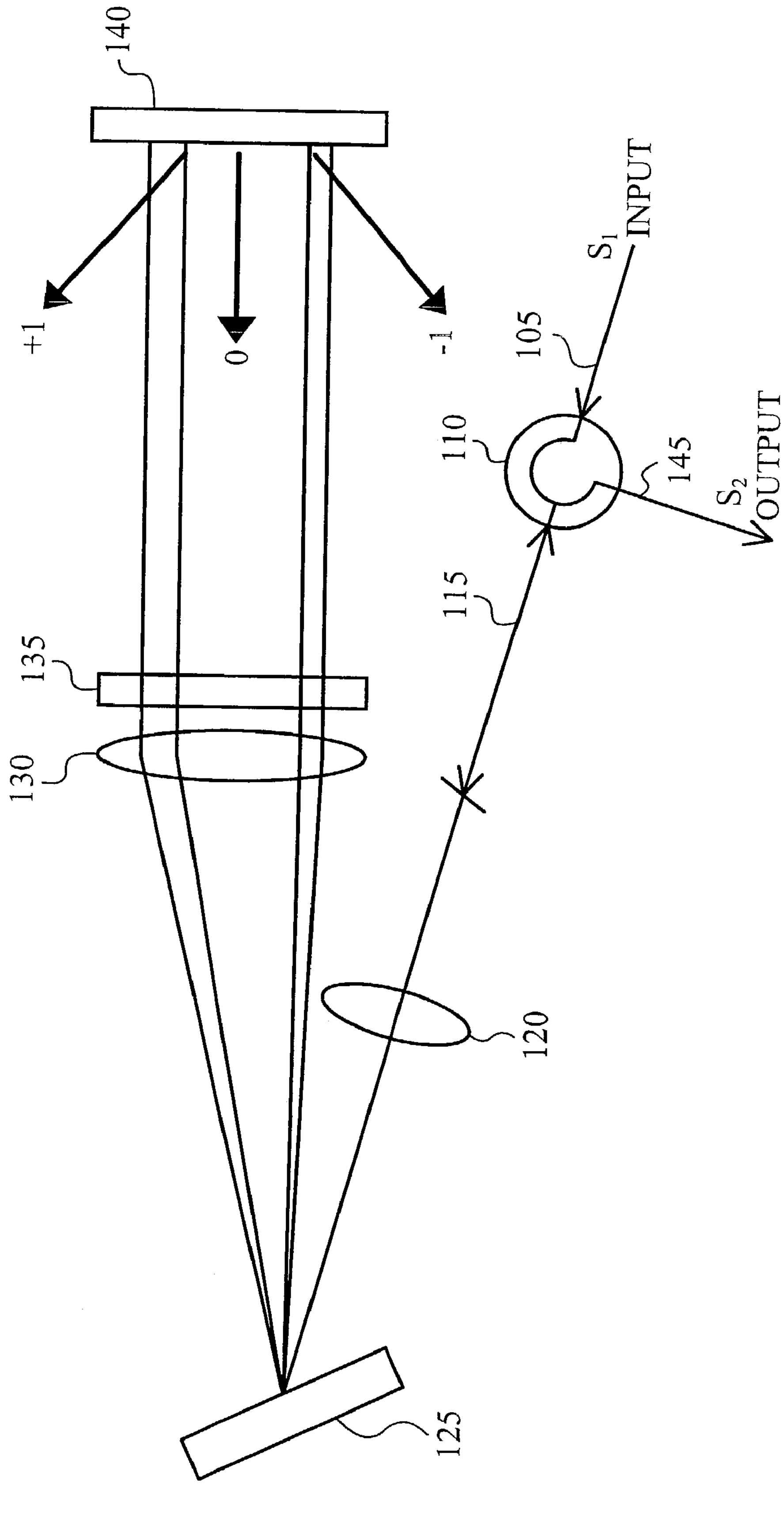

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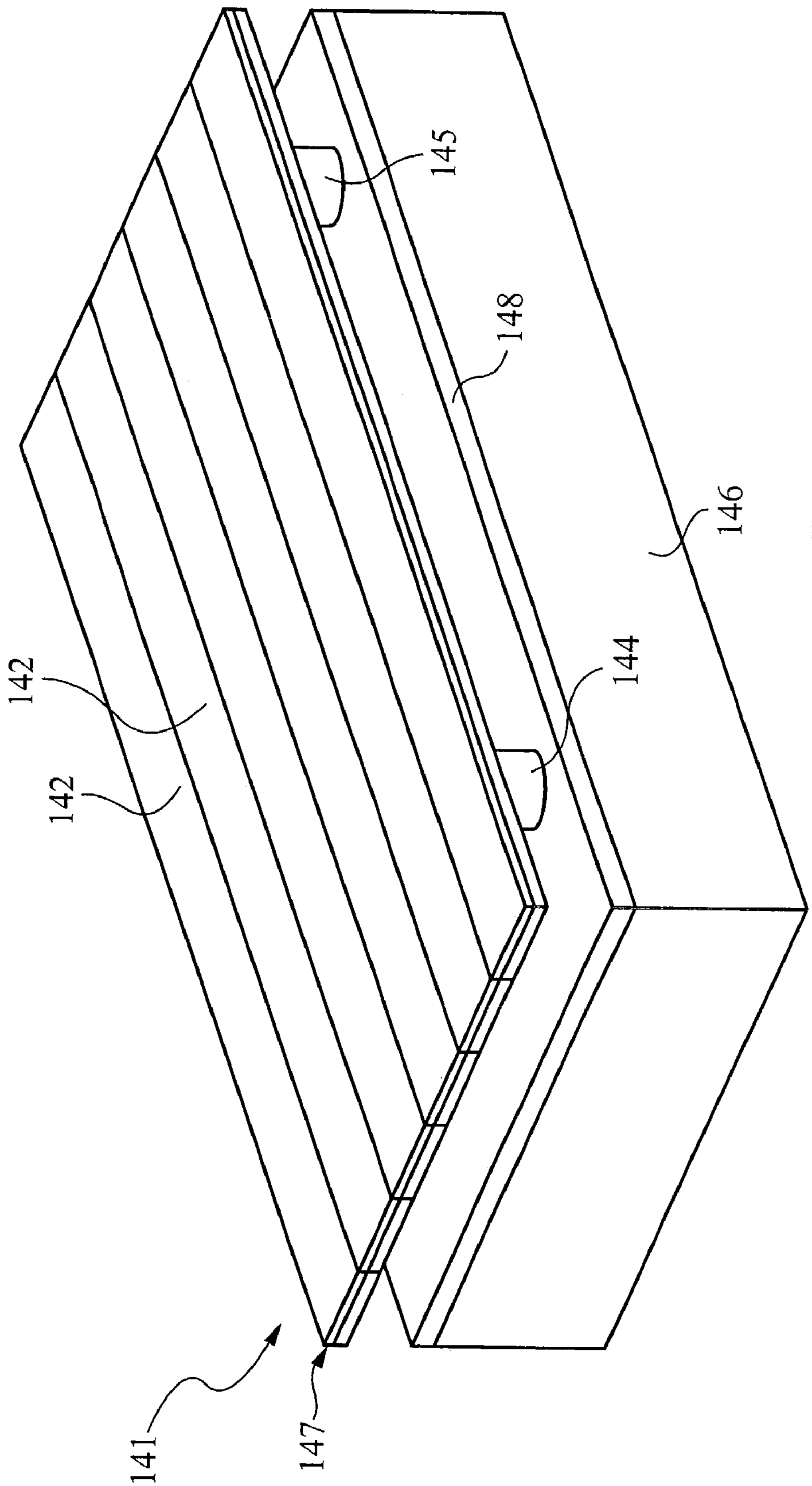

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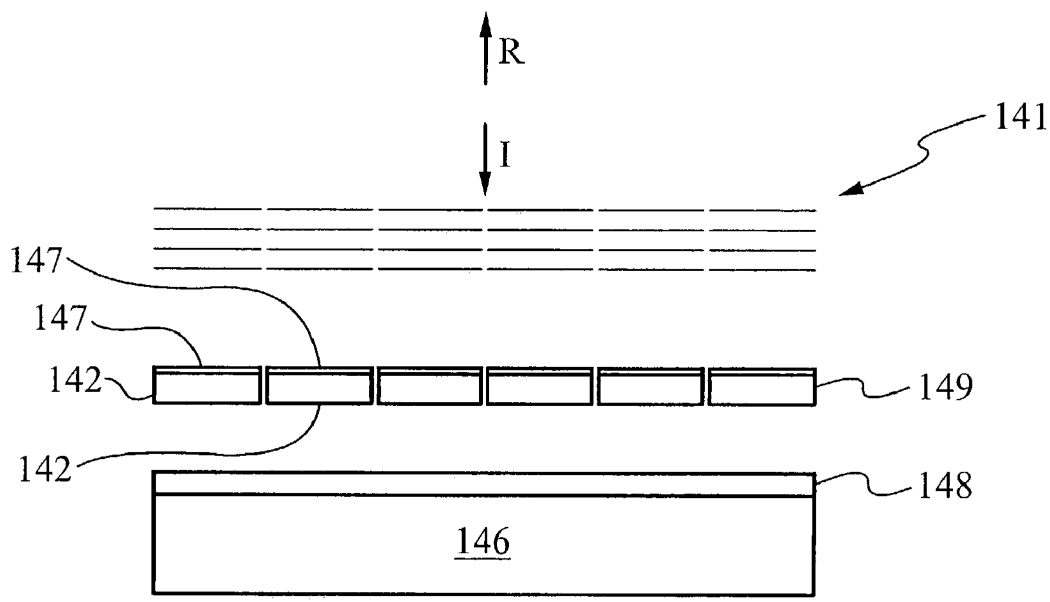

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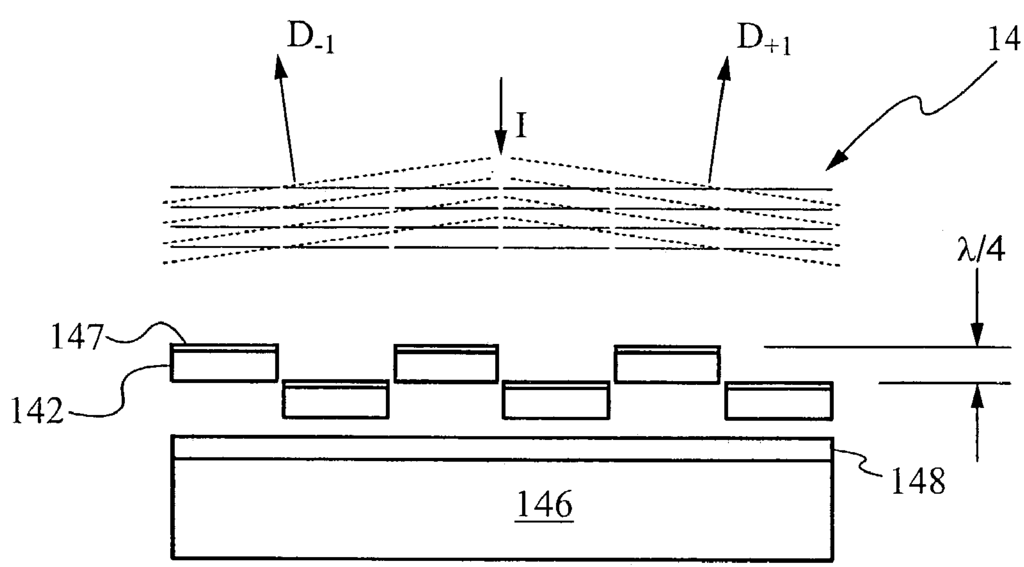

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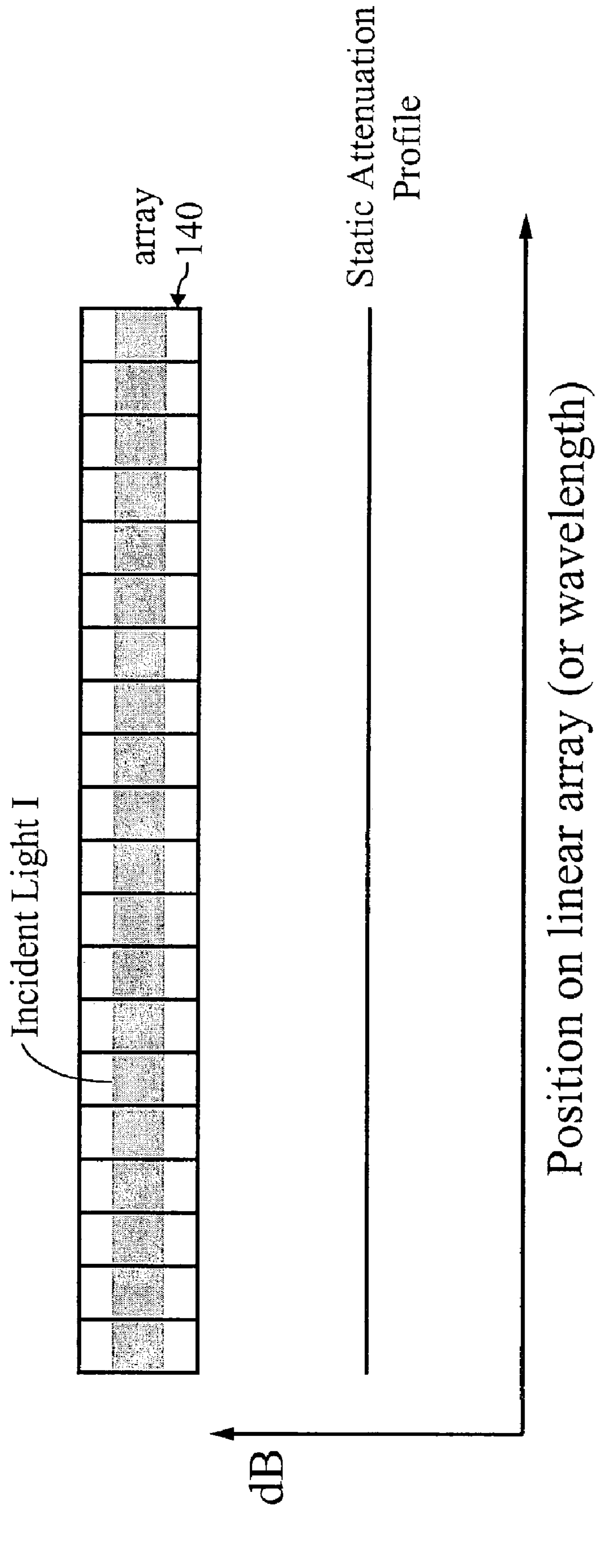
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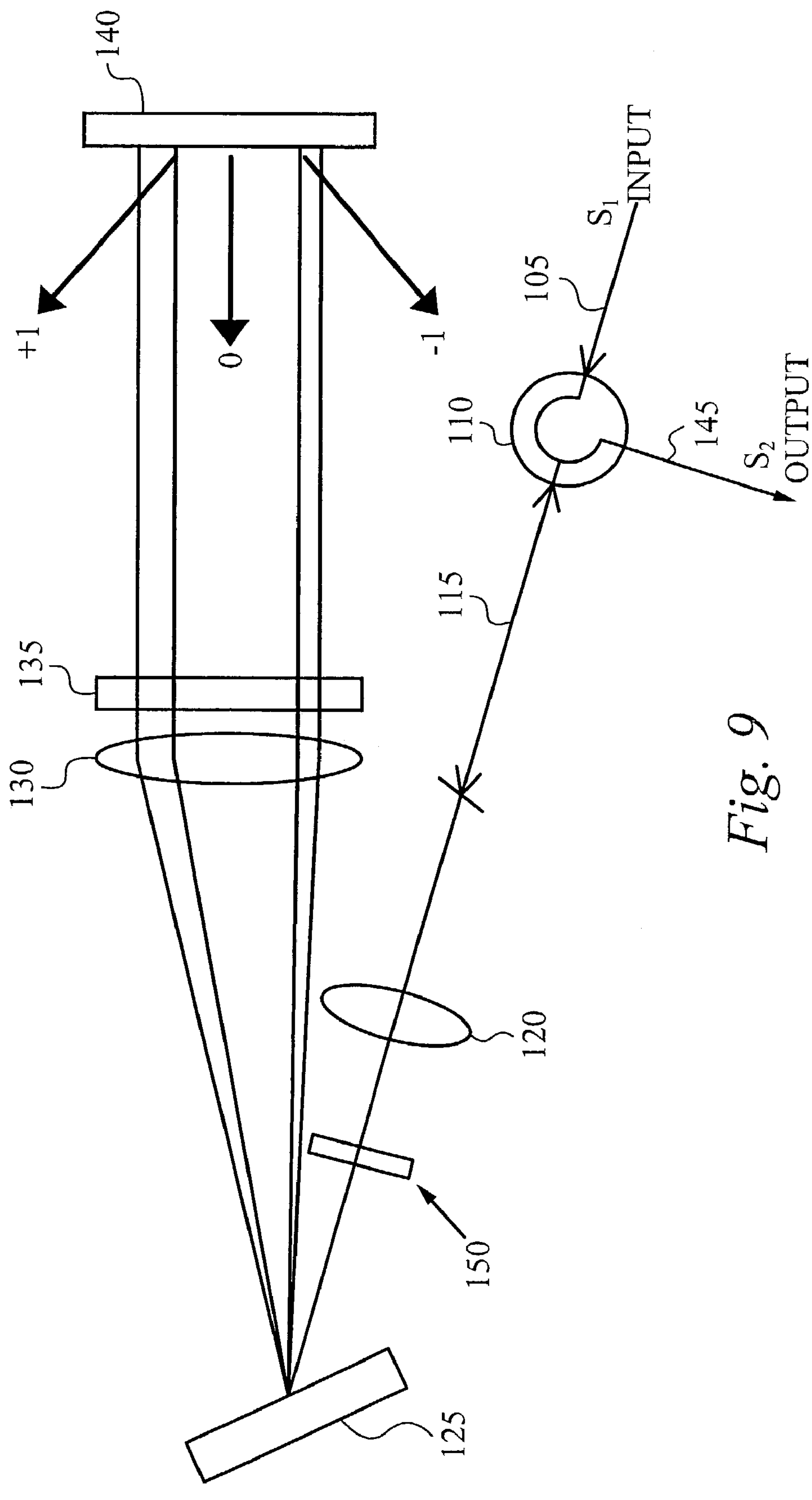
Static Attenuation
Profile
Incident Light I
Position on linear array (or wavelength)
dB

Fig. 8



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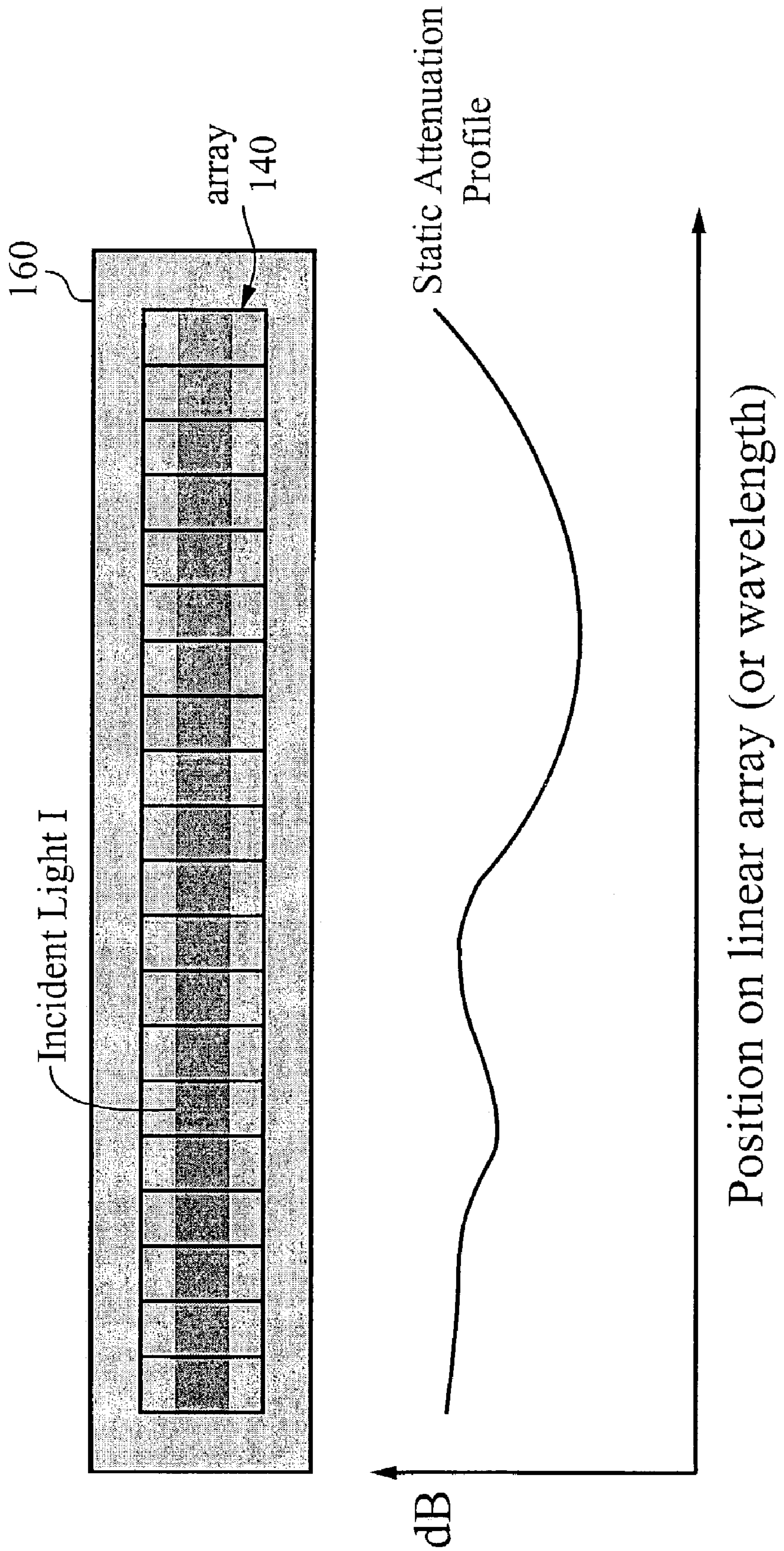
160
array 140
Incident Light I
Static Attenuation Profile
dB
Position on linear array (or wavelength)

Fig. 10

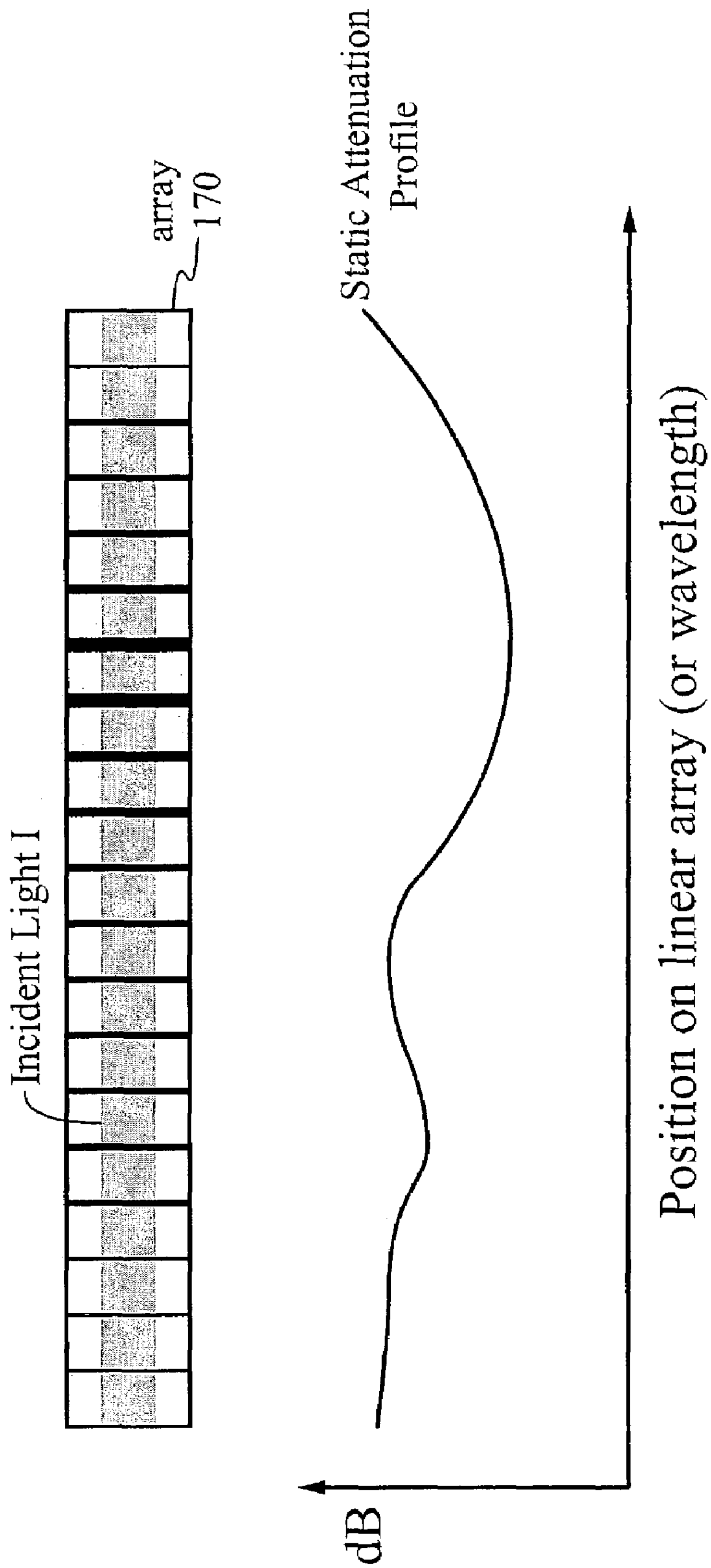
array 170
Static Attenuation Profile
Incident Light I
dB
Position on linear array (or wavelength)

Fig. 11

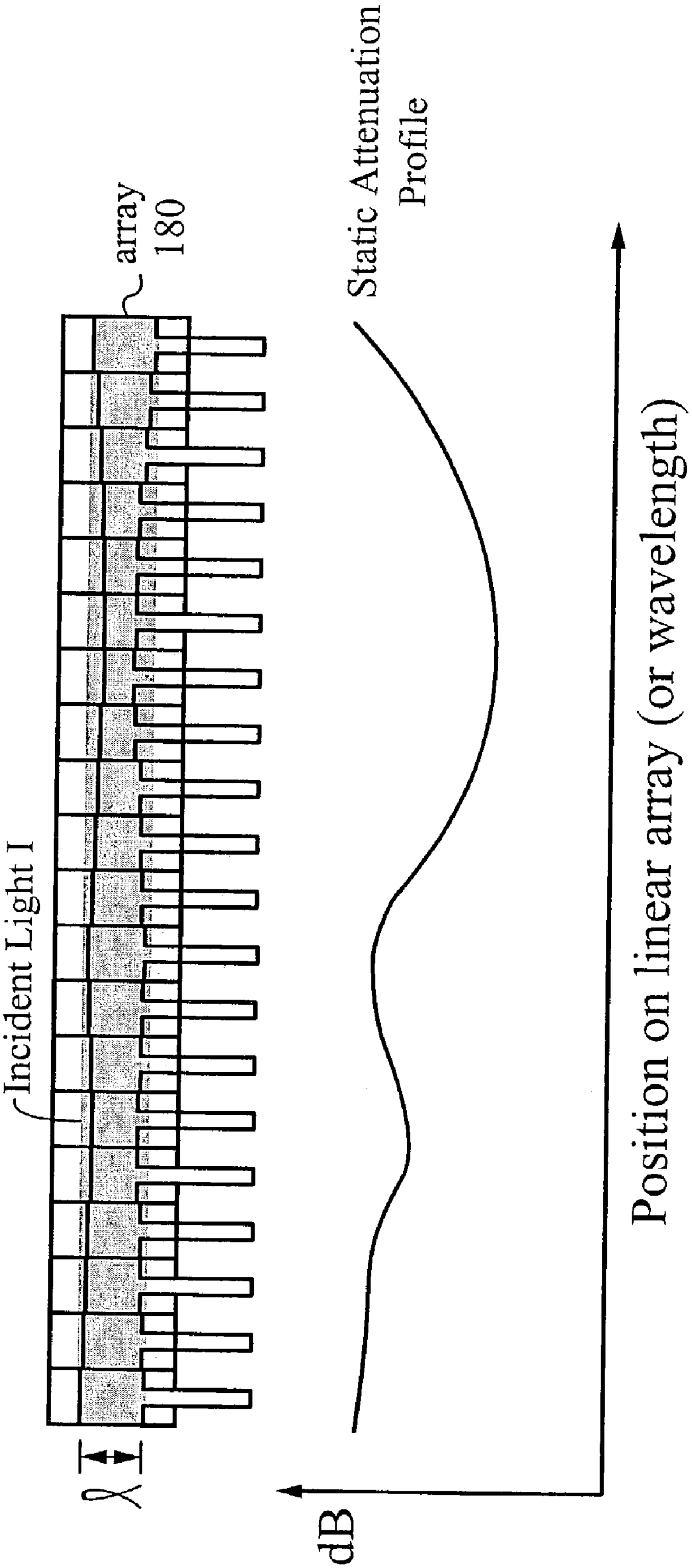
array
180
Static Attenuation
Profile
Incident Light I
λ
dB
Position on linear array (or wavelength)

Fig. 12

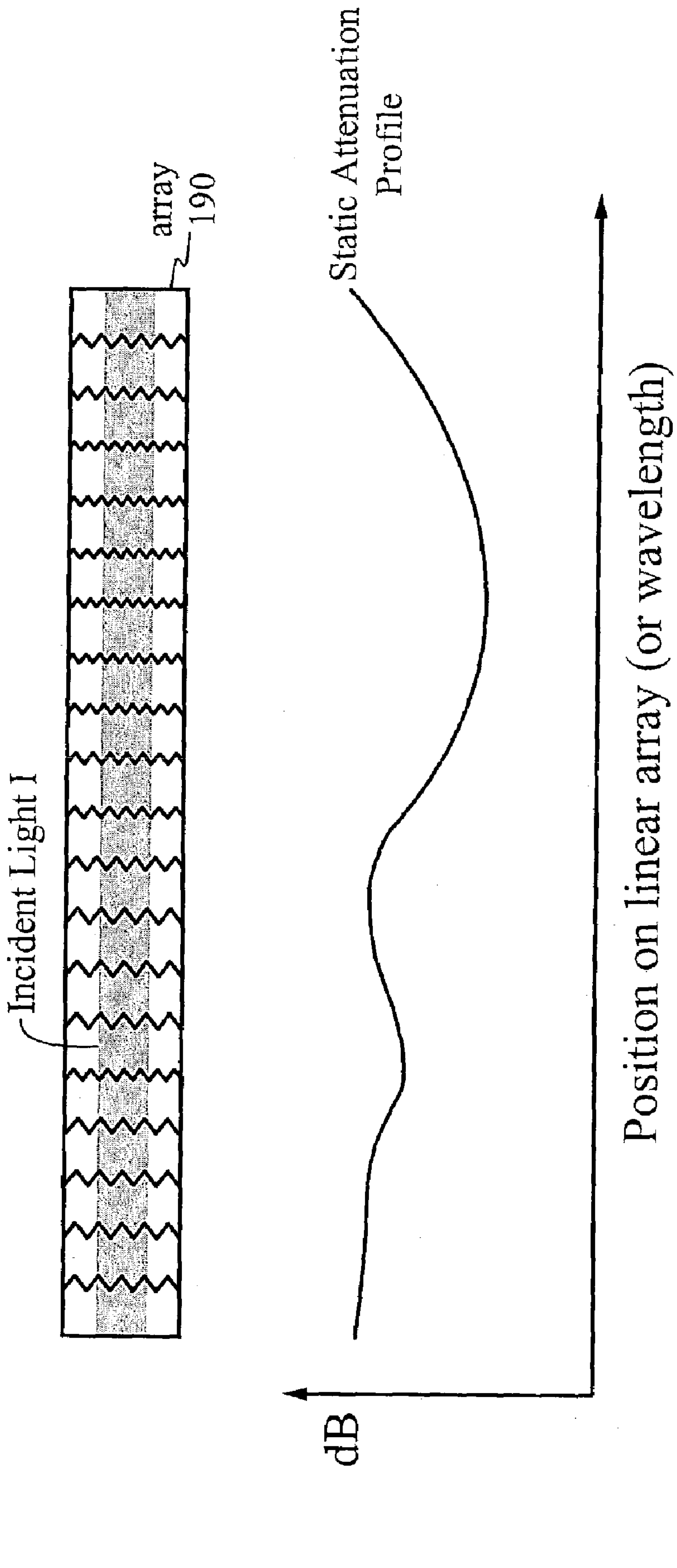
array
190
Static Attenuation
Profile
Incident Light I
dB
Position on linear array (or wavelength)

Fig. 13

TWO-STAGE GAIN EQUALIZER

FIELD OF THE INVENTION

The present invention relates to a method of and an apparatus for gain equalizing. More particularly, this invention relates to a two-stage gain equalizer including static attenuation and dynamic attenuation.

BACKGROUND OF THE INVENTION

In modem wavelength division multiplexed (WDM) optical transmission systems, there is a need to dynamically equalize the gain of the various data-carrying channels as they pass through the optical network. A large number of factors, including attenuation through the fiber itself, unequal amplification as a function of wavelength as the channels pass through cascaded Erbium Doped Fiber Amplifiers (EDFAs), and others contribute to channel qualities that can degrade the performance and bit-error rate of the system overall. A Dynamic Gain Equalizer (DGE) module equalizes WDM channels or groups of channels to ensure optimal amplification and optical signal-to-noise ratio (OSNR), thus minimizing the bit-error rate (BER) for each channel, while extending transmission distance and expanding usable bandwidth.

Historically, the chief contributor to gain unevenness has been the EDFA. Due to the inherent gain response of the EDFA's operation, there is always a modest imbalance in the gain applied as a function of wavelength. In typical network applications, multiple EDFAs are employed along the total span of the network to boost the signal as it is attenuated through the fiber. As each of the EDFAs imparts a characteristic gain profile to the band, the total unevenness increases in an additive manner. The net result after several EDFAs can be a wholly objectionable power imbalance across the various channels in the band.

In order to compensate for this effect, manufacturers of EDFAs typically insert a static optical element called a Gain Flattening Filter (GFF) into the optical path inside their EDFA modules. A GFF is typically manufactured by depositing a large number of thin films onto a piece of optical glass. The characteristics of the thin films (their thickness and indices of refraction, for example) are carefully selected and controlled during deposition such that they create optical resonances and interferences that effect the transmission of light as a function of wavelength. If properly designed, a GFF can be created in such a way that it completely offsets the effects of the EDFA for a given total input power.

FIGS. **1A**-**1C** illustrate the effect of a GFF attenuation profile on an EDFA gain profile. FIG. **1A** illustrates a representation of a gain profile of a typical EDFA. The gain profile indicates how different wavelength signals are attenuated to varying degrees as the signals are impacted by the EDFA. FIG. **1B** illustrates an attenuation profile of a typical GFF used to offset the effects of the EDFA imparting the gain profile illustrated in FIG. **1A**. Ideally, the attenuation profile of a GFF will be the inverse of the gain profile of a corresponding EDFA. FIG. **1C** illustrates the resultant gain of an EDFA with GFF where the EDFA includes the gain profile of FIG. **1A** and the GFF includes the attenuation profile of FIG. **1C**. A flat resultant gain, as illustrated in FIG. **1C**, indicates that the GFF completely offsets the power imbalance effects of the EDFA.

In practice, however, there are a number of factors which render the simple "EDFA plus GFF" formula inadequate. First, while EDFAs have characteristic gain profiles, there can be some manufacturing variability between unit-to-unit and lot-to-lot. The GFFs are even more notoriously difficult to manufacture with consistent performance, due to the large number of different thin films that must be deposited with high repeatability and consistency. Small changes in manufacturing conditions can result in significant changes in performance, making the GFF both expensive and inconsistent. The films on the GFFs can also bleach over their lifetime, rendering them less effective over time. Furthermore, in modern optical networks, where specific optical channels may be frequently dropped or added, there is a need to dynamically effect the gain profile. The profile of the EDFA changes as a result of total power, so as channels are added or dropped, the profile itself changes. A solution that relies wholly upon a static GFF cannot provide adequate flatness to satisfy these changing network requirements.

DGEs have been proposed as a next-generation substitute for GFFs. Because they are variable, they can be configured in the field to optimally flatten a specific set of EDFAs after they are actually powered up. Because they are dynamic, they can respond to changing network conditions as channels are added and dropped.

A number of factors effect the design of the DGE. For example, the DGE should have adequate dynamic range and attenuation slope to flatten the total gain imbalance in the system. Generally, the greater the dynamic range and attenuation slope of the DGE, the greater the number of EDFAs that can be cascaded. As EDFAs are added to lengthen a single optical span, each EDFA adds its characteristic gain imbalance, requiring greater dynamic range and attenuation slope at the DGE for compensation. Thus, there is a rather direct con-elation between the dynamic range and attenuation slope of the DGE and the length of the optical span than can be achieved.

As a practical matter, however, the desire to increase the dynamic range of the DGE can be offset by other factors. For example, it may be more expensive to implement a DGE with wide dynamic range. A DGE that is designed to have a wide dynamic range may induce greater insertion losses when operating in its transparent, or non-attenuation, mode. When operated close to the limit of its dynamic range, a DGE may exhibit degraded performance in terms of polarization dependent losses (PDL), chromatic dispersion or other objectionable effects.

What is needed is a gain equalizer that dynamically attenuates and increases the dynamic range, but does so at a lower cost.

What is needed is a gain equalizer that dynamically attenuates and increases the dynamic range, but does so without significantly increasing deleterious effects such as PDL and insertion loss.

SUMMARY OF THE INVENTION

In one aspect of the present invention, an apparatus selectively adjusts power levels of component signals of a wavelength division multiplexed signal. The apparatus comprises a first filter and a second filter. The first filter modulates the component signals according to a static attenuation profile, thereby providing coarsely modulated component signals. The second filter is coupled to the first filter to receive the coarsely modulated component signals and to modulate the coarsely modulated component signals according to a dynamic attenuation profile, thereby providing finely modulated component signals.

In another aspect of the present invention, a light modulator selectively adjusts power levels of component signals of a wavelength division multiplexed signal. The light modulator comprises a plurality of elements selectively operable in a first mode and a second mode. The plurality of elements are configured to continually apply a predetermined static attenuation profile. When in the first mode, the component signals are modulated according to the static attenuation profile, thereby providing coarsely modulated component signals. When in the second mode, the component signals are modulated according to the static attenuation profile and a dynamic attenuation profile, thereby providing finely modulated component signals.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates a representation of a gain profile of a typical EDFA.

FIG. **1**B illustrates an attenuation profile of a typical GFF used to offset the effects of the EDFA imparting the gain profile illustrated in FIG. **1**A.

FIG. **1**C illustrates the resultant gain of an EDFA with GFF where the EDFA includes the gain profile of FIG. **1**A and the GFF includes the attenuation profile of FIG. **1**C.

FIG. **2** illustrates the additive effect of an integrated device according to an embodiment of the present invention.

FIG. **3** illustrates an attenuation profile of a two-stage gain equalizer according to an embodiment of the present invention

FIG. **4** illustrates a preferred embodiment of the DGE.

FIG. **5** illustrates a grating light valve type device of the preferred two-stage gain equalizer of the present invention.

FIG. **6** illustrates a cross-section of the grating light valve type device in a reflection mode.

FIG. **7** illustrates a cross-section of the grating light valve type device in a diffraction mode.

FIG. **8** illustrates a top-down view of the grating light valve array of FIGS. **5-8** and its corresponding attenuation profile.

FIG. **9** illustrates a first embodiment of the two-stage gain equalizer according to the present invention and its corresponding attenuation profile.

FIG. **10** illustrates a second embodiment of the two-phase gain equalizer of the present invention and its corresponding attenuation profile.

FIG. **11** illustrates a third embodiment of the two-phase gain equalizer of the present invention and its corresponding attenuation profile.

FIG. **12** illustrates a fourth embodiment of the two-phase gain equalizer of the present invention and its corresponding attenuation profile.

FIG. **13** illustrates a fifth embodiment of the two-phase gain equalizer of the present invention and its corresponding attenuation profile.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The present invention overcomes the aforementioned deficiencies of the background art by providing a two-stage gain equalizer. In a first stage, a static filter comprising a static attenuation profile performs a coarse modulation on a received WDM signal, thereby providing a coarsely modulated WDM signal. Then, in a second stage, a dynamic filter comprising a dynamic gain profile performs a fine modulation on the coarsely modulated WDM signal, thereby providing a finely modulated WDM signal. The dynamic filter preferably includes a dynamic gain equalizer (DGE), and more preferably, the DGE includes a spatial light modulator. Preferably, the spatial light modulator comprises a grating light valve type device (GLV type device). Preferably, the static filter comprises a filter with static GFF-like functionality. In this manner, the two-stage integrated gain equalizer of the present invention first removes a predictable first order unevenness within a given gain profile of the WDM signal, and then fine-tunes the removal of the remaining unevenness utilizing a DGE.

There are a number of advantages of a DGE with integrated GFF functionality. The first advantage is a wider overall gain capability. FIG. **2** illustrates the additive effect of an integrated device according to the embodiments of the present invention. If a static filter has an attenuation range of 10 dB, for example, and a dynamic filter has an attenuation range of 12 dB, then the combined effect can be additive. That is, the combined attenuation range of an integrated static and dynamic filter is 22 dB in this case.

In a practical sense, data collected from various EDFAs indicates a range of potential gain profile curves. In designing the two-stage gain equalizer of the present invention, the most conservative gain profile is considered. The inverse of the most conservative gain profile is used as the attenuation profile of the static filter. This is done because in a best case scenario, at least the attenuation of the most conservative gain profile must be performed in order to obtain gain flattening. In many cases, a given EDFA includes a gain profile showing greater gain than the most conservative gain profile, yet falls within the known range of gain profiles. In this case, the portion of the gain profile that is greater than the most conservative gain profile is attenuated by the dynamic filter of the present invention. In known cases, a given EDFA imparts at least as much gain as the most conservative gain profile. A portion of the gain profile that corresponds to the most conservative gain profile is attenuated statically by the static filter. The remaining portion is attenuated dynamically, which accounts for the variances in the gain profiles for all EDFAs. Although this concept is applied to gain profiles associated with EDFAs, it should be clear that the concept of the present invention can also be applied to gain profiles associated with other types of amplifiers.

A second advantage of the two-stage gain equalizer is a higher degree of accuracy provided by the dynamic filter. Instead of combining the ranges of the static and dynamic filters to widen the overall gain capability, the dynamic range of the DGE can be reduced to improve its accuracy. To better illustrate this point, refer to FIG. **3**. FIG. **3** illustrates an attenuation profile of a two-stage gain equalizer according to the present invention as it is applied to an exemplary gain profile of a given EDFA. It should be clear that the gain profile illustrated in FIG. **3** is for a random EDFA and that the attenuation profile can be designed to take any required shape depending upon the nature of the amplification device. It should also be clear that although the amplification device is an EDFA, the principles of the present invention can be applied to gain profiles imparted by other amplification devices. The specific gain profile and subsequent explanation of the corresponding attenuation profile as illustrated in FIG. **3** are to aid in understanding and should not limit the scope of the present invention.

A gain profile **10** is a data point for a specific EDFA. As discussed above, a range of gain profiles exists for all known EDFAs. This range includes a most conservative gain profile, or a minimum gain profile **15**, and a maximum gain profile **20**. As is clear from FIG. **3**, the gain profile **10** lies between the minimum gain profile **15** and the maximum gain profile **20**. In designing the two-stage gain equalizer, the maximum possible gain must be accounted for in the event that the actual gain profile hits this maximum. This maximum possible gain is represented in FIG. **3** at point A. If a desired resultant gain is represented by a resultant gain **50**, then the maximum possible range at point A is range R. Range R is the difference between the gain at point A and the desired resultant gain, at the same wavelength. Within the DGE, there are drive electronics that enable the spatial light modulator to modulate an incident light beam in a step-wise function. The drive electronics essentially take a maximum attenuation corresponding to the maximum possible gain and divides it by a discrete number of steps. If for example, the drive electronics use 8 bits to represent these discrete steps, the number of discrete steps is 256. More or less steps can be designed into the DGE. Where the DGE is to attenuate the entire maximum possible gain, range R, then the size of each discrete step, also known as a step width, is R/256. In general, the larger the step width, the less accurate the DGE is in attenuating a signal to a desired level. In the case where a discrete signal, represented in FIG. **3** at point C, is to be attenuated to the resultant gain **50**, a larger step width makes it less likely that the DGE will attenuate the signal exactly to the resultant gain **50**. Instead, it is more likely that the closest step is slightly higher or slightly lower than the resultant gain **50**.

However, by using a static filter with GFF-like functionality before using the DGE, the DGE will no longer need to attenuate the entire maximum possible gain, range R. By reducing the necessary attenuation range, the step width of the DGE is reduced, thereby improving the attenuation accuracy. The static filter includes a static attenuation profile **30** that approximates the inverse of the minimum gain profile **15**. It is a design intent that the static filter attenuates a static portion **40** corresponding to a portion of the gain profile **10** that corresponds to the minimum gain profile **15**. Once the static filter is applied, the DGE need only attenuate a dynamic portion **45** that corresponds to a remaining portion of the gain profile **10**. It should be clear from FIG. **3** that the entire dynamic portion **45** is only applied when the gain profile **10** is the maximum gain profile **20**. In the case where the gain profile **10** is less than the maximum gain profile **20**, only a portion of dynamic portion **45** is utilized by the DGE. Since the static filter attenuates a range S corresponding to the minimum gain profile **15**, the necessary maximum dynamic attenuation range is no longer range R. Instead, the maximum dynamic attenuation range is range R minus range S, which results in range D. By first using the static filter, the step width of the DGE can be reduced to a range D/256. Since range D is smaller than range R, the step width is reduced. The smaller step width produces finer resolution, which results in improved attenuation accuracy by the DGE. The step width described above is defined in relation to range D, which conforms to the known range of gain profiles for EDFAs. However, it should be clear that the range of the DGE can be smaller or larger than the range D depending on the design specifications of the system.

By first using a static filter, a two-stage gain equalizer can be designed to either increase the overall attenuation range or improve the overall attenuation accuracy. If the intention is to increase the overall attenuation range, then the step width for the DGE remains the same as if the DGE where operating without the static filter. In this case, the attenuation capabilities of the static filter and the dynamic filter are additive and the overall attenuation range is increased. If, on the other hand, the intention is to improve attenuation accuracy, then the step width is reduced, thereby refining the resolution of the DGE. Clearly, there is a trade-off between overall attenuation range and attenuation resolution. Just as clearly, the two-stage gain equalizer of the present invention can be designed to meet any necessary specification that lies between the maximum and minimum values for these trade-offs.

A third advantage of the two-stage gain equalizer is the ability to avoid using the extreme range of the DGE component. The DGE includes the spatial light modulator, preferably a grating light valve type device. Spatial light modulators, and grating light valve type devices in particular, modulate light using diffraction. In a non-attenuating state, the spatial light modulator acts as a flat mirror. In this state, effects due to PDL, insertion loss and others, are minimized. However, once elements of the spatial light modulator are actuated, diffraction occurs. As diffraction increases, so do the deleterious effects associated with PDL. Maximum diffraction, as well as maximum PDL, occurs at the extreme range of the DGE. When designing a DGE, the worst case scenario for PDL must be accounted for in device specifications. So, if by including a static filter the necessary extreme range of the DGE is reduced, then the specifications accounting for PDL, and other deleterious effects that worsen near the extreme end of the range of the device are improved.

For example, if a system includes a 15 dB specification for total dynamic range and the system only includes a DGE, then the entire 15 dB is to be attenuated by the DGE. On the other hand, if a static filter comprising a 5 dB range is first used, then the DGE need only attenuate 10 dB. For the DGE, a 15 dB dynamic range entails a more severe design constraint than a 10 dB dynamic range. So, when a design specification calls for a challenging total dynamic range, there are trade-offs between achieving the total dynamic range and introducing PDL, excessive insertion loss, etc. Therefore, if the dynamic range can be relieved, then other design specifications can be more easily or better achieved.

A fourth advantage of the two-stage gain equalizer is that deleterious effects such as PDL, insertion loss, etc. are more evenly distributed across the wavelength spectrum. Certain effects of the DGE, such as PDL, can be plotted as a function of attenuation. In the case of no attenuation there is typically only a minimal amount of PDL. As attenuation is increased, PDL worsens as some function of a characteristic response. In the case of a DGE, an attenuation profile is applied as a corrective function for a given gain profile. For any portion of the gain profile that has a relatively steep gain-to-wavelength slope, there is a correspondingly steep attenuation-to-wavelength slope of the attenuation profile. For a portion of the attenuation profile that has a steep attenuation-to-wavelength slope, neighboring wavelengths will have significantly different PDL since the neighboring wavelengths experience significantly different attenuations. Similar variances exist for other deleterious effects such as insertion loss, etc. Instead, if a GFF-like static filter is first applied, the slope of the attenuation profile for the DGE is much less steep. This can be seen in FIG. **3**. Notice that the dynamic portion **45** has a much more constant range than that of the entire attenuation profile **35**. A more constant range leads to a flatter attenuation profile, and therefore a flatter slope, attributable to the DGE. With a flatter slope, neighboring wavelengths experience more similar PDL. As a result, the PDL across the wavelength spectrum is more evenly distributed, which is desirable.

A fifth advantage of the two-stage gain equalizer is that some degree of gain equalizing will occur even in the case of a power failure. A DGE is inoperative during power failure, however, a GFF is not power dependent. Therefore, during loss of power the static attenuation profile is still applied.

A sixth advantage of the two-stage gain equalizer is that the production specifications of the static filter can be relaxed. In an ideal case, the static filter completely predicts the nominal unevenness of the gain profile. If the static filter is used as the sole means for attenuating a given gain profile, then the attenuation profile of the static filter must be precisely manufactured to exactly offset the gain profile. In the case of the two-stage gain equalizer, the attenuation profile of the static filter only needs to be close to completely offsetting the given gain profile, where the dynamic filter can "make up the difference" for any discrepancy.

Preferably, within the two-stage gain equalizer of the present invention, the dynamic filter is a dynamic gain equalizer (DGE). Such a DGE is described in U.S. application Ser. No. 10/051,972 filed on Jan. 15, 2002, and entitled "METHOD AND APPARATUS FOR DYNAMIC EQUALIZATION IN WAVELENGTH DIVISION MULTIPLEXING" which is hereby incorporated by reference. FIG. **4** illustrates a preferred embodiment of the DGE. A WDM signal **S1** entering port **105** of a circulator **110** is output at port **115** to a collimating lens **120**. The collimated signal **S1** is then transmitted to a bidirectional diffraction grating **125**, where component wavelengths $\lambda_1, \ldots, \lambda_n$ of the signal S1 are diffracted at different angles. Although a diffractive grating is preferably used to de-multiplex the signal S1 into component wavelengths $\lambda_1, \ldots, \lambda_n$ alternative means can be used, including but not limited to a prism and a bi-directional demultiplexor A transform lens **130** maps the component wavelengths $\lambda_1, \ldots, \lambda_n$ onto different positions of a diffractive light modulator **140** via a quarter wave plate **135**. Preferably, the diffractive light modulator **140** is a grating light valve type device (GLV type device) array onto which each of the component wavelengths $\lambda_1, \ldots, \lambda_n$ is mapped to a particular grating light valve type device within the grating light valve type device array. The GLV type device array **140** is an addressable dynamic diffraction grating array. By adjusting the amount of diffraction, the reflected power can be controlled accurately over a large dynamic range. The reflected light returns along the same path into port **115** and finally out port **145** via circulator **110** as output signal S2.

A grating light valve type device **141** within the GLV type device array **140** according to one aspect of the embodiments of the present invention is illustrated in FIG. **5**. The grating light valve type device **141** preferably comprises elongated elements **142** suspended by first and second posts, **144** and **145**, above a substrate **146**. The elongated elements **142** comprise a conducting and reflecting surface **147**. The substrate **146** comprises a conductor **148**. In operation, the grating light valve type device **141** operates to produce modulated light selected from a reflection mode and a diffraction mode.

It will be readily apparent to one skilled in the art that the conducting and reflecting surface **147** can be replaced by a multilayer dielectric reflector in which case a conducting element would also be included in each of the elongated elements **142**. Further, it will be readily apparent to one skilled in the art that the conducting and reflecting surface **147** can be coated with a transparent layer such as an anti-reflective layer.

FIGS. **6** and **7** illustrate a cross-section of the grating light valve type device **141** in a reflection mode and a diffraction mode, respectively. The elongated elements **142** comprise the conducting and reflecting surface **147** and a resilient material **149**. The substrate **146** comprises the conductor **148**. In operation, the grating light valve type device **141** operates to produce modulated light selected from a reflection mode and a diffraction mode.

FIG. **6** depicts the grating light valve type device **141** in the reflection mode. In the reflection mode, the conducting and reflecting surfaces **147** of the elongated elements **142** form a plane so that incident light I reflects from the elongated elements **142** to produce reflected light R.

FIG. **7** depicts the grating light valve type device **141** in the diffraction mode. In the diffraction mode, an electrical bias causes alternate ones of the elongated elements **142** to move toward the substrate **146**. The electrical bias is applied between the reflecting and conducting surfaces **147** of the alternate ones of the elongated elements **142** and the conductor **148**. The electrical bias results in a height difference between the alternate ones of the elongated elements **142** and non-biased ones of the elongated elements **142**. A height difference of a quarter wavelength A/4 of the incident light I produces maximum diffracted light including plus one and minus one diffraction orders, D_{+1} and D_{-1}.

FIGS. **6** and **7** depict the grating light valve type device **141** in the reflection and diffraction modes, respectively. For a deflection of the alternate ones of the elongated elements **142** of less than a quarter wavelength $\lambda/4$, the incident light I both reflects and diffracts producing the reflected light R and the diffracted light including the plus one and minus one diffraction orders, D_{+1} and D_{-1}. In other words, by deflecting the alternate ones of the elongated elements less the quarter wavelength $\lambda/4$, the grating light valve type device **141** produces a variable reflectivity. By varying the reflectivity in this manner, each wavelength can be equalized as desired. It should be born in mind that terms like "equalize" and "equalization" as used with respect to embodiments of the present invention are to be broadly interpreted with respect to regulating the power levels of component light signals to any pre-determined level of relative power levels. Accordingly, the term "equalize" as used herein is not to be limited to any one particular curve or ratio, but simply constitutes a regulation or normalization of signal power against any pre-determined curve or ratio of power levels at different frequencies.

While FIGS. **6** and **7** depict the grating light valve type device **141** having six of the elongated elements **142**, the grating light valve type device **141** preferably includes more of the elongated elements **142**. By providing more of the elongated elements **142**, the elongated elements **142** are able to function as groups, which are referred to as pixels. Preferably, the pixels are groups of six of the elongated elements **142**. Alternatively, the pixels are groups of more or less elongated elements **142**.

It will be readily apparent to one skilled in the art that the term "pixel" is used here in the context of an element of a light modulator rather than its more common definition of a picture element of a display.

Referring back to FIG. **4**, as each of the component wavelengths $\lambda_1, \ldots, \lambda_n$ interact with the GLV type device array **140**, they experience diffraction. A benefit of diffraction is that a certain amount of light is "thrown away" from the central path. In this manner, the light mapped onto the GLV type device array **140** is dynamically attenuated by the performance of the GLV type device array **140**. As each wavelengths $\lambda_1, \ldots, \lambda_n$ impinges the GLV type device array **140**, the grating light valve type device corresponding to each particular wavelength causes all, some, or none of the of the impinging light to diffract. In essence, each of the component wavelengths$\lambda_1, \ldots, \lambda_n$ is dynamically equalized by discarding all, some, or none of the signal by diffraction. As the elongated elements of a grating light valve type device are deflected, the light mapped to that grating light valve type device is diffracted by an amount corresponding to the distance that the elongated elements are deflected, resulting in only a portion of the component wavelength being reflected. When the elongated elements are not deflected, none of the impinging light is diffracted and the entire component wavelength is reflected. Through this process, each reflected component wavelength is dynamically equalized.

The attenuating function of the GLV type device array **140** can have any arbitrary shape along the array. The attenuating function can be a smoothly varying arbitrary shape, a passband filter for one or more channels, or any other desired function. A given attenuation function of the DGE is herein referred to as an attenuation profile.

FIG. **8** illustrates a top-down view of the GLV type device array **140** along with its non-actuated attenuation profile. The non-actuated attenuation profile is also referred to as a static attenuation profile. Non-actuating indicates that the GLV type device array **140** is in the reflection mode, or mirror-state. In other words, the static attenuation profile shown in FIG. **8** illustrates the GLV type device array **140** acting as a static filter. The flat resultant output of the static attenuation profile illustrated in FIG. **8** indicates that the GLV type device array **140** does not attenuate the impinging light while in a static mode.

FIGS. **9-13** illustrate various embodiments of the two-stage gain equalizer of the present invention. Each of the embodiments are described as including a linear GLV type device as the dynamic attenuating element. It is readily perceived that other types of spatial light modulators can easily be substituted for the GLV type device, and the same concepts still apply. The static attenuation profiles illustrated in each of the FIGS. **10-13** are for illustrative purposes only and are not intended to limit the scope of the present invention.

FIG. **9** illustrates a first embodiment of the two-stage gain equalizer according to the present invention. A static filter **150** is inserted into the optical path of the DGE illustrated in FIG. **4**. Preferably, the static filter **150** is a GFF, although any static filter including GFF-like functionality can be used. The static filter **150** is preferably positioned between the collimating lens **120** and the diffraction grating **125** so that the static filter **150** receives collimated light. Alternatively, the static filter **150** can be positioned anywhere within the optical train illustrated in FIG. **9**. Since the static filter **150** is used in conjunction with a DGE, normal tolerances for thin-film optical GFFs need not be observed, thereby lowering the cost of the GFF element. Because the static filter **150** can be readily inserted into the sealed environment of a pre-existing DGE package, the overall cost of adding the static filter **150** to the system can also be reduced.

FIG. **10** illustrates a second embodiment of the two-phase gain equalizer of the present invention. Instead of inserting the static filter **150** as in FIG. **9**, a static filter **160** is used as a lid that hermetically seals the GLV type device array **140**. Preferably, the static filter **160** is a GFF, although any static filter including GFF-like functionality can be used. The GLV type device array **140** illustrated in FIG. **4** includes a transparent glass lid comprising anti-reflection coatings. In the second embodiment, a stack of thin-film coatings is applied to the glass lid before the glass lid is sealed onto the GLV type device array **140**. In this manner, the glass lid with thin-film coatings acts as a GFF. As in the first embodiment, tolerances on the optical GFF element are reduced, so costs can also be reduced. By integrating the GFF with the GLV type device array, this second embodiment has one less optical component in the system than the first embodiment. This reduces cost and complexity since the GFF no longer needs to be mounted and aligned as a separate optical element. The static attenuation profile of the second embodiment is illustrated in FIG. **10**. The static attenuation profile is determined while the GLV type device array **140** is non-actuated. Therefore, the static portion of the resultant output attributable to the GLV type device array **140** is the same as that illustrated in FIG. **8**. So the static attenuation profile in FIG. **10** can be solely attributable to the static filter **160**.

FIG. **11** illustrates a third and preferred embodiment of the two-stage gain equalizer of the present invention. A GLV type device array **170** is designed to impart a static and dynamic attenuation profile. In the third embodiment, the GLV type device array **170** replaces the GLV type device array **140** and static filter **150** of the first embodiment and replaces the GLV type device array **140** and the static filter **160** of the second embodiment. In the GLV type device array **170**, the gaps between the GLV type device ribbons, or elements, are varied as a means to produce a static attenuation profile that can be varied along the length of the array. As the gaps are widened, the width of the adjacent ribbon is narrowed by a corresponding amount. This effect can be seen in FIG. **11**. As described herein, an increase or decrease in the gap width indicates a corresponding decrease or increase in the adjacent ribbon width, respectively. The gaps are specified as part of the GLV type device manufacturing process. As such, the static attenuation profile that results from the varied gap widths is a fixed characteristic of the GLV type device array. By varying the gaps between the GLV type device elements, the GLV type device array **170** imparts the static, or fixed, attenuation profile without actuating the elements of the GLV type device array **170**. This static attenuation profile is illustrated in FIG. **11**. The wider the gaps, the larger the attenuation. Although the GLV type device array **170** illustrated in FIG. **11** indicates that the gaps between adjacent GLV type device ribbons are varied, this is also meant to indicate that the gaps between the elements within a specific GLV type device pixel or minimum addressable element are also varied. Preferably, all gaps between elements in the same GLV type device addressable element are the same. Alternatively, the gaps between elements in the same GLV type device addressable element can also be varied to further refine the attenuation profile.

Photolithography is used to produce the varied gap widths. In contrast, GFF-like static filters are produced by depositing thin-film optical coatings. Such thin-films are difficult to manufacture within specifications and they tend to bleach over time. Using photolithography tightens control and repeatability. Including the GFF-like functionality within the design of the GLV type device reduces cost and increases the useful life of the device. There is no incremental cost penalty associated with fabricating the device using photolithography, and the additional GFF-like static filter is removed.

Accurate design of the GLV type device must take into account reflectivity of the base at each of the gaps. While attenuation does increase as the gap widens, there is a limit. If the gap is increased to its maximum, which correlates to a GLV type device ribbon width of zero, the Fresnal reflection from the base is approximately 30%. The use of dielectric layers, diffraction structures, etc. can be used to better suppress the reflection. Considering the negative attenuation effects due to base reflectivity and that there is a maximum achievable attenuation, varying the gap width may not produce enough attenuation to optimally meet the minimum static attenuation profile. In this case, the dynamic range of the DGE can be increased to compensate for the shortfall of the static attenuation profile.

For the GLV type device array **170** illustrated in FIG. **11**, widening the gaps alters PDL effects across the GLV type device array. For applications that are PDL sensitive, the GLV type device array **170** can be altered to greatly minimize these PDL effects. Instead of the ribbons being linear, the ribbons are cut as curved surfaces, in a serpentine-like pattern. Since the ribbons form a serpentine pattern, so do the gaps. These serpentine gaps can be varied in width similarly to the gap widths in the GLV type device array **170** illustrated in FIG. **11**. In this manner, the serpentine gap widths can be varied to achieve a desired static attenuation profile while also minimizing PDL effects.

The concept of varying gap width to produce a static attenuation profile can be broadened beyond GLV type devices. Any type of physical media performing dynamic attenuation where excess insertion losses are produced as a function of its operation can vary the element that causes the excess insertion loss to create a static attenuation profile. In the case of the GLV type device, the gaps lead to excess insertion loss. This concept can also be used in LCDs that have cell gaps between each LCD, to MEMS mirrors that have gaps between the mirrors, and other types of similar devices.

FIG. **12** illustrates a fourth embodiment of the two-stage gain equalizer of the present invention. Similar to the third embodiment, a GLV type device array **180** is designed to impart a static and dynamic attenuation profile. In the fourth embodiment, the GLV type device array **180** replaces the GLV type device array **140** and either the static filter **150** or **160** of the first or second embodiments, respectively. In contrast to the GLV type device array **170**, the gaps between the GLV type device ribbons of the GLV type device array **180** are constant, but the amount of reflective coating on each GLV type device ribbon is varied as a means to produce an attenuation profile that can be varied along the length of the array. The reflective layer which overcoats each of the GLV type device ribbons is patterned in such a way that it only reflects a portion of the incident light. By changing the coverage of the reflective coating that is applied to each GLV type device ribbon, the degree of attenuation of the element, or ribbon, can be varied along the length of the GLV type device array **180**. Although the GLV type device array **180** illustrated in FIG. **12** indicates that the amount of reflective coating on each of the adjacent GLV type device ribbons is varied, this is also meant to indicate that the amount of reflective coating on each of the elements within a specific GLV type device pixel or minimum addressable element are also varied. Preferably, the amount of reflective coating on each of the elements in the same GLV type device addressable element are the same. Alternatively, the amount of reflective coating on each of the elements in the same GLV type device addressable element can also be varied to further refine the attenuation profile.

The reflective layer patterns are specified as part of the GLV type device manufacturing process. As such, the static attenuation profile that results from the varied reflective layer patterns is a fixed characteristic of the GLV type device array. By varying the length l of the reflective layers on the GLV type device elements, as illustrated in FIG. **12**, the GLV type device array **180** imparts a static, or fixed, attenuation profile without actuating the elements of the GLV type device array **180**. This static attenuation profile is illustrated in FIG. **12**. In the previous embodiments, the reflective layer on each GLV type device of the GLV type device arrays **140** and **170** sufficiently covers the length of each ribbon such that the entire incident light impinges the reflective layer. In the GLV type device array **180**, the length l of the reflective layer on each ribbon is patterned such that the reflective area on each ribbon receives all or only a portion of the incident light. The effective reflective area is altered geometrically to configure to the desired static attenuation of the incident light. The more reflective area on the ribbon means more of the incident light is reflected, thereby limiting the degree of attenuation. The less reflective area on the ribbon means less of the incident light is reflected, which leads to greater attenuation. By varying the reflective area on the ribbons, a desired static attenuation profile is achieved.

Similar to the third embodiment, varying the reflective area on each ribbon is performed using photolithography. As above, this approach introduces no additional costs, and eliminates the GFF-like static filter. Tighter calibration specifications are necessary to ensure proper optical alignment of the incident light on the GLV type device array. Alignment of the incident light can be achieved using active alignment with feedback.

FIG. **13** illustrates a fifth embodiment of the two-stage gain equalizer of the present invention. Similar to the third and fourth embodiments, a GLV type device array **190** is designed to impart a static and dynamic attenuation profile. In the fifth embodiment, the GLV type device array **190** replaces the GLV type device array **140** and either the static filter **150** or **160** of the first or second embodiments, respectively. In contrast to the GLV type device arrays **170** and **180**, the gaps between the GLV type device ribbons and the reflective area on each ribbon of the GLV type device array **190** are constant, but the edges of each ribbon are serrated as a means to produce an attenuation profile that can be varied along the length of the array. Although the GLV type device array **190** illustrated in FIG. **13** indicates that the serration frequency between adjacent GLV type devices is varied, this is also meant to indicate that the serration frequency between the elements within a specific GLV type device are also varied. Preferably, all serration frequencies between elements in the same GLV type device are the same. Alternatively, the serration frequency between elements in the same GLV type device can also be varied to further refine the attenuation profile.

As can be seen in FIG. **13**, the edges between ribbons is cut in such a way that light is diffracted at angles 45 degrees away from the long axis of the GLV type device array **190**. By changing the pitch of the edge serrations, the magnitude of the light that is diffracted out of an optical collection system can be varied, thereby changing the attenuation along the length of the array. In other words, by changing the frequency of the serrations, the amount of light that is diffracted, and therefore collected, is changed. The higher the serration frequency, the greater the attenuation, as illustrated by the static attenuation profile in FIG. **13**.

As with the third and fourth embodiments, the fifth embodiment is achieved using photolithography which comes without penalties of cost or additional optical elements. The GLV type device array **190** includes a further advantage of being symmetrical in the X-axis and the Y-axis of the array, thereby avoiding introduction of any problems with PDL that can arise when the two orthogonal polarizations are effected differently.

It will be readily apparent to one skilled in the art that other various modifications may be made to the preferred embodiment without departing from the spirit and scope of the invention as defined by the appended claims.

We claim:

1. An apparatus for selectively adjusting power levels of component signals of a wavelength division multiplexed (WDM) signal, the apparatus comprising:

a circulator configured to receive the WDM signal via a first port and outputting the WDM signal via a second port;

a collimating lens configured to receive the WDM signal from the circulator and to collimate the WDM signal;

a first filter for receiving the WDM signal from the collimating lens and for modulating the component signals according to a static attenuation profile, thereby providing coarsely modulated component signals, wherein the static attenuation profile includes a predetermined function in which attenuation varies as a function of the wavelength of the component signal;

a de-multiplexing device configured to receive the coarsely-modulated component signals from the first filter and for diffracting the coarsely-modulated component signals at different angles;

a transform lens configured to receive the diffracted coarsely-modulated signals from the de-multiplexing device and to map the coarsely-modulated signals onto different positions in a plane; and

a second filter configured in the plane to receive the coarsely-modulated component signals mapped to the different positions in the plane and to modulate the coarsely-modulated component signals according to a dynamic attenuation profile, thereby providing finely-modulated component signals, wherein the second filter includes a dynamic gain equalizer comprising a diffractive light modulator, the diffractive light modulator including a plurality of elements configured to receive de-multiplexed component signals, wherein each element is controllable to selectively modulate each of the component signals according to the dynamic attenuation profile,

wherein the first filter comprises a transparent glass lid with thin-film coatings covering the diffractive light modulator of the second filter.

2. The apparatus according to claim **1** wherein the diffractive light modulator comprises a grating light valve device.

3. The apparatus according to claim **1** wherein the first filter includes a Gain Flattening Filter.

4. The apparatus according to claim **3** wherein the Gain Flattening Filter is separate from the light modulator.

5. The apparatus according to claim **1** wherein the diffractive light modulator comprises a plurality of MEMS elements.

6. The apparatus according to claim **1** wherein the diffractive light modulator comprises a plurality of liquid crystal elements.

7. The apparatus of claim **1**, wherein the de-multiplexing device comprises a bidirectional diffraction grating.

8. The apparatus of claim **1**, wherein the de-multiplexing device comprises a prism.

9. The apparatus of claim **1**, wherein the de-multiplexing device comprises a bidirectional de-multiplexor.

10. The apparatus of claim **1**, further comprising a quarter wave plate positioned between the transform lens and the second filter.

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