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(54) **OPTICAL FIBER LINK WITH PRIMARY AND COMPENSATING OPTICAL FIBERS**

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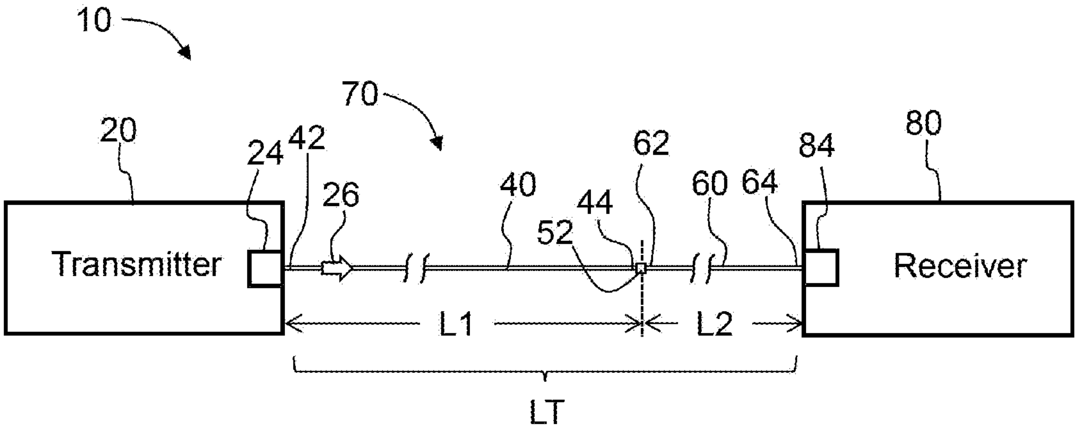
USPC **385/31**; 385/124

(57) **ABSTRACT**

An optical fiber link that utilizes concatenated primary and compensating multimode optical fibers is disclosed. The primary optical fiber has a first relative refractive index profile with a first alpha value α_{40} of about 2.1 that provides for a minimum amount of intermodal dispersion of guided modes at a peak wavelength λ_{P40} in the range from 840 nm to 860 nm, and has a first bandwidth BW_{40} of 2 GHz·km or greater. The compensating optical fiber has a second relative refractive index profile with a second alpha value α_{60}, and wherein $-0.9 \le (\alpha_{60} - \alpha_{40}) \le -0.1$, and a peak wavelength λ_{P60} greater than 880 nm. The optical fiber link has improved bandwidth and data rates for first and second optical signals within first and second wavelength ranges, respectively.



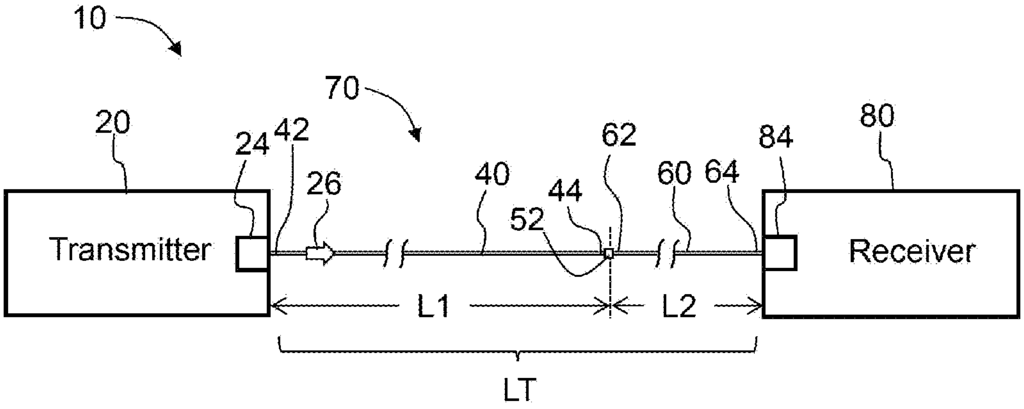

10
70
20
24
42
26
40
44
52
62
60
64
84
80
Transmitter
Receiver
L1
L2
LT

FIG. 1A

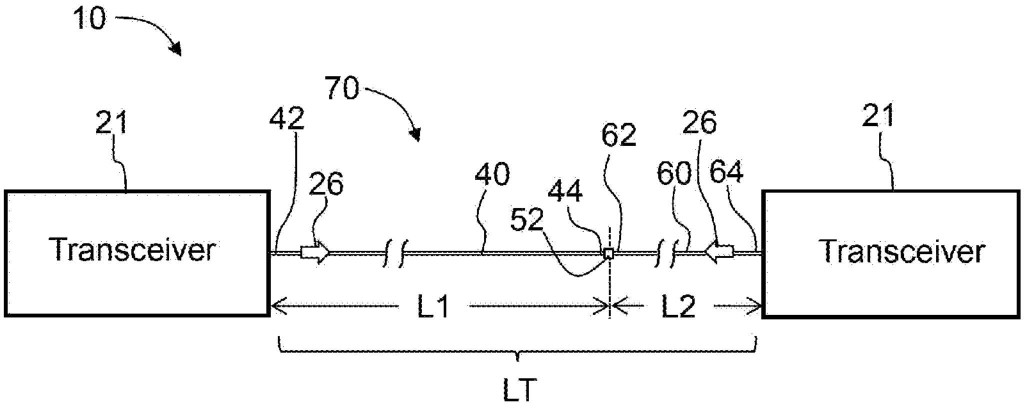

10
70
21
42
26
40
44
52
62
60
26
64
21
Transceiver
Transceiver
L1
L2
LT

FIG. 1B

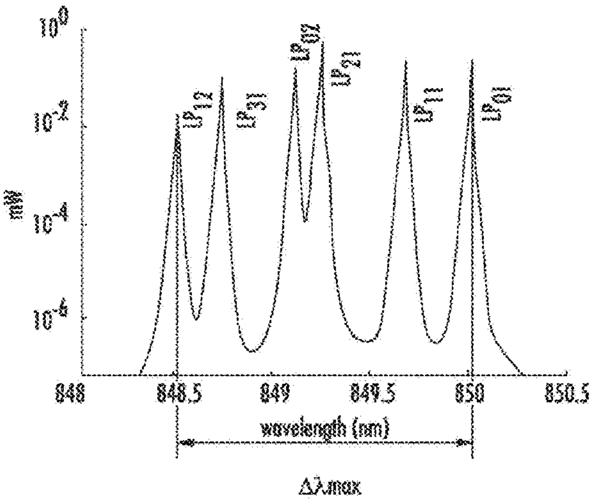


FIG. 2

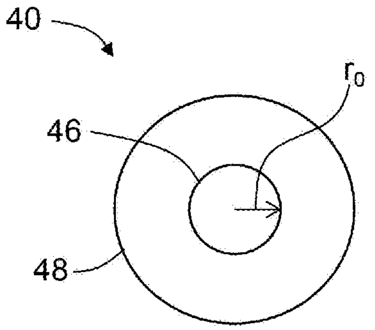


FIG. 3A

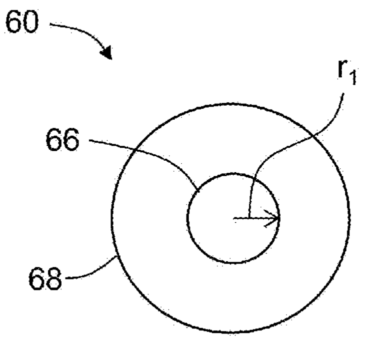


FIG. 3B

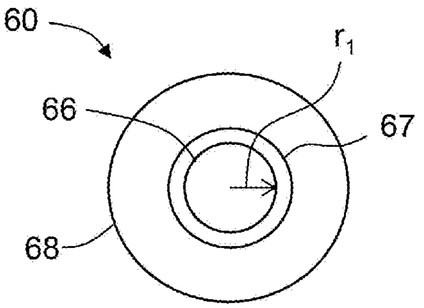


FIG. 3C

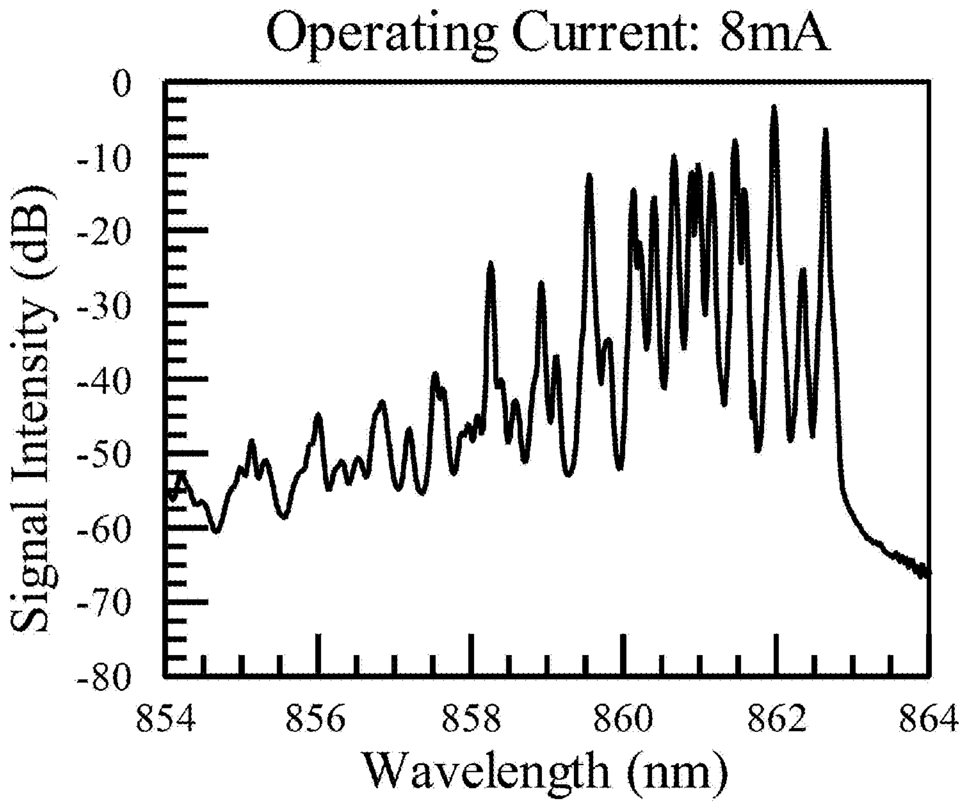

Operating Current: 8mA
Signal Intensity (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
854
856
858
860
862
864
Wavelength (nm)

FIG. 4

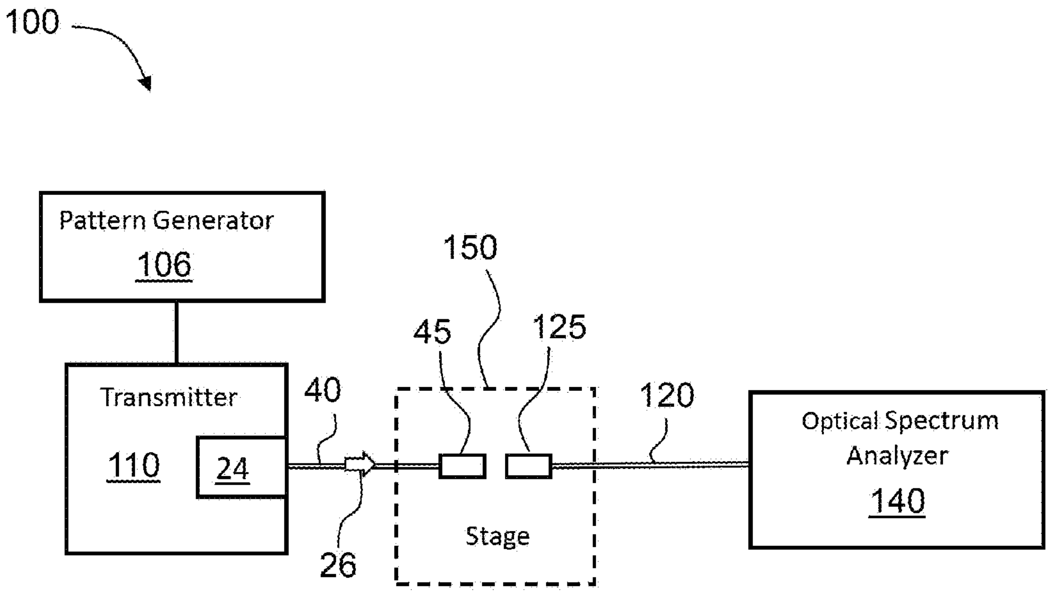

100
Pattern Generator
106
Transmitter
110
24
40
26
150
45
125
Stage
120
Optical Spectrum
Analyzer
140

FIG. 5

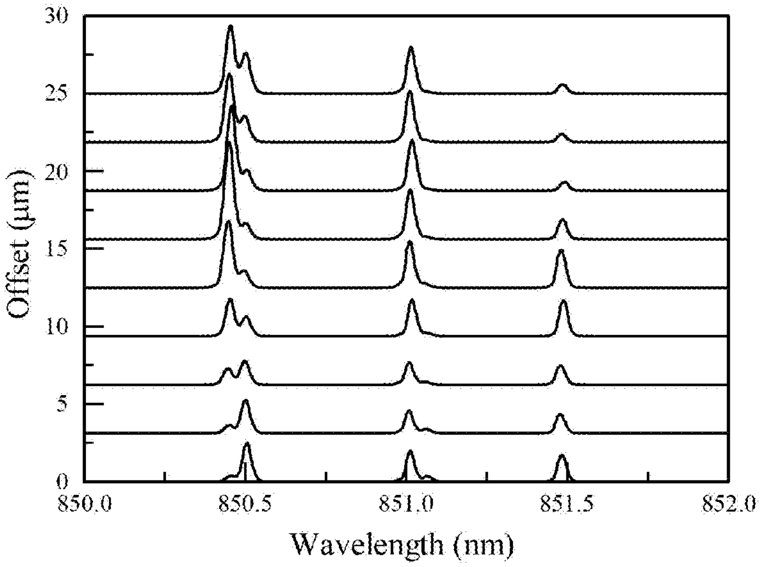

30
25
20
15
10
5
0
Offset (μm)
850.0
850.5
851.0
851.5
852.0
Wavelength (nm)

FIG. 6

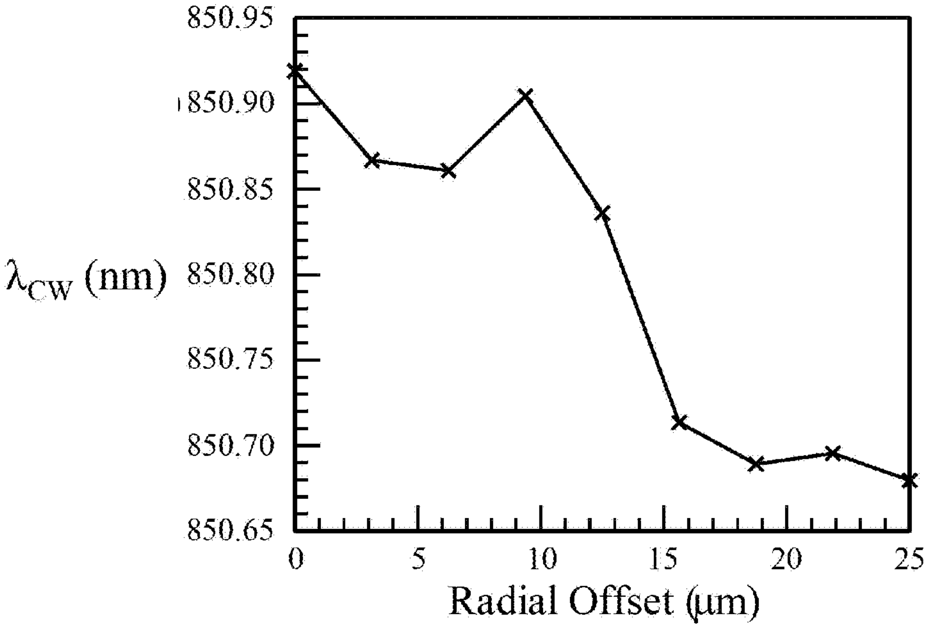

850.95
850.90
850.85
850.80
850.75
850.70
850.65
λ_{CW} (nm)
0
5
10
15
20
25
Radial Offset (μm)

FIG. 7

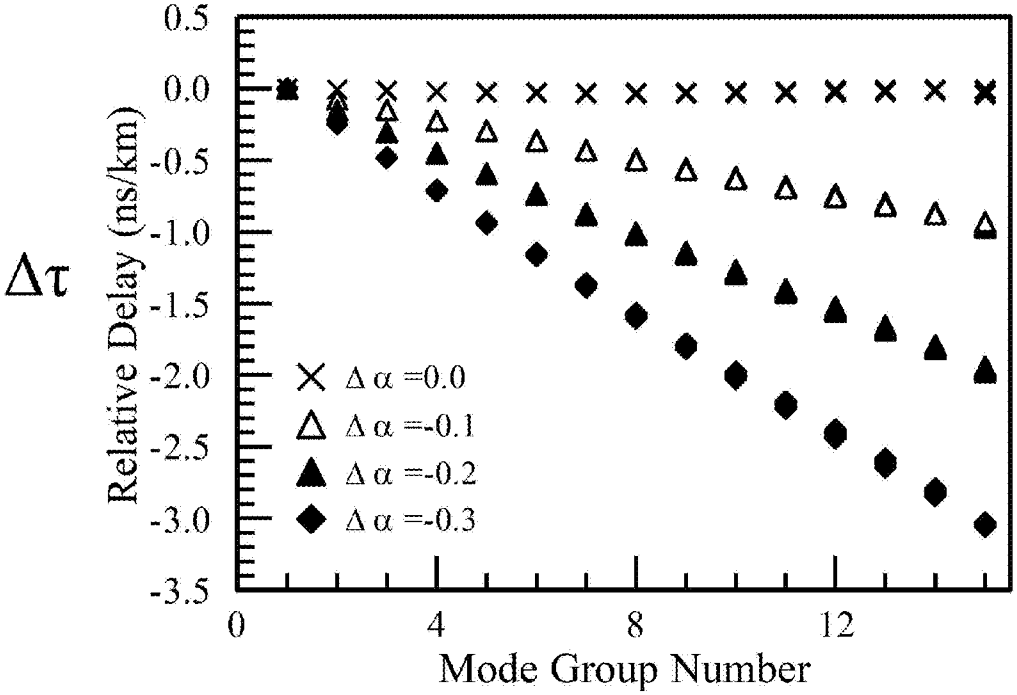

Δτ
Relative Delay (ns/km)
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
0
4
8
12
Mode Group Number
× Δα =0.0
△ Δα =-0.1
▲ Δα =-0.2
◆ Δα =-0.3

FIG. 8

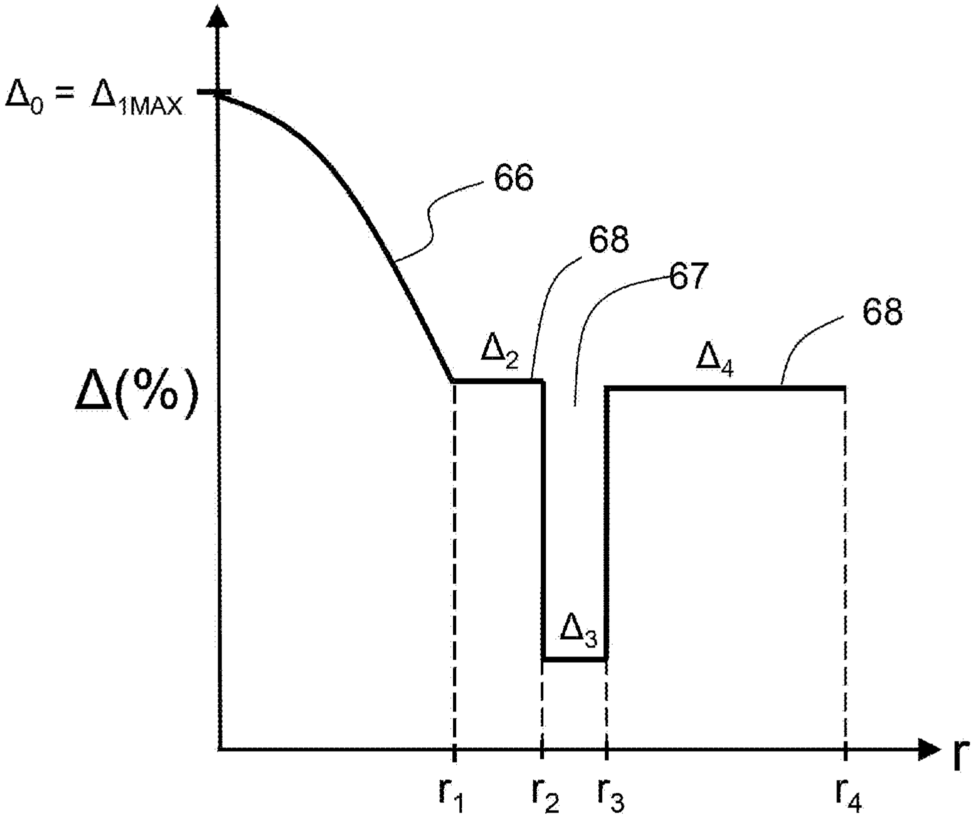

$\Delta_0 = \Delta_{1MAX}$
66
68
67
68
Δ_2
Δ_4
$\Delta(\%)$
Δ_3
r
r_1
r_2
r_3
r_4

FIG. 9

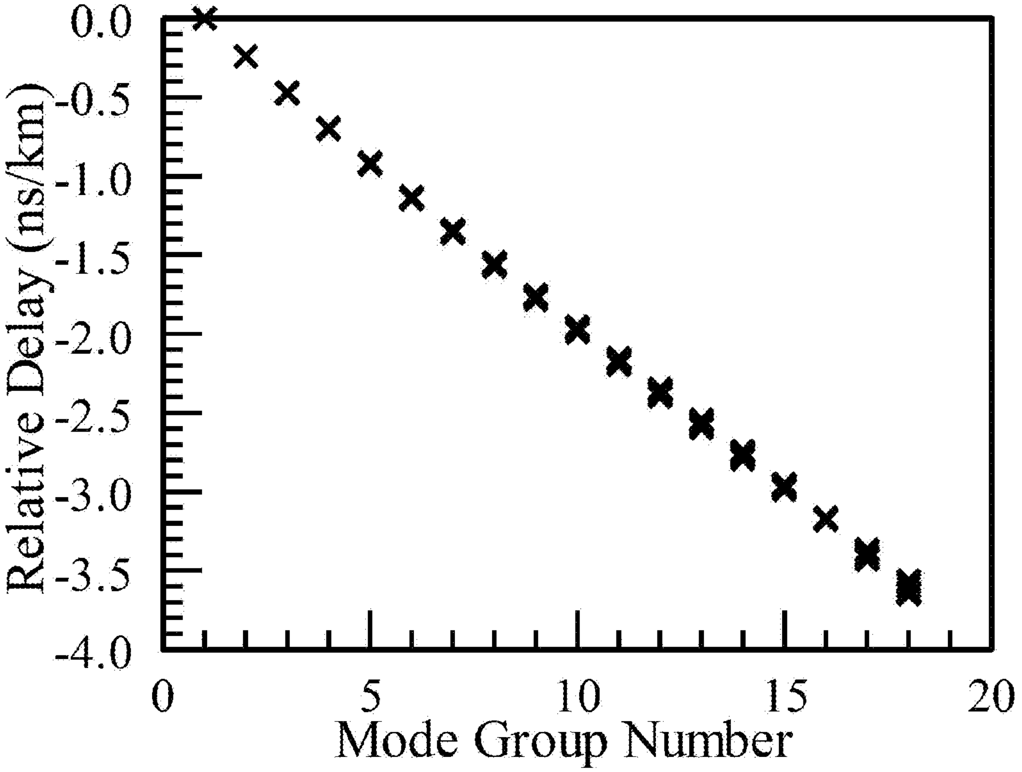

0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
Relative Delay (ns/km)
0
5
10
15
20
Mode Group Number

FIG. 10

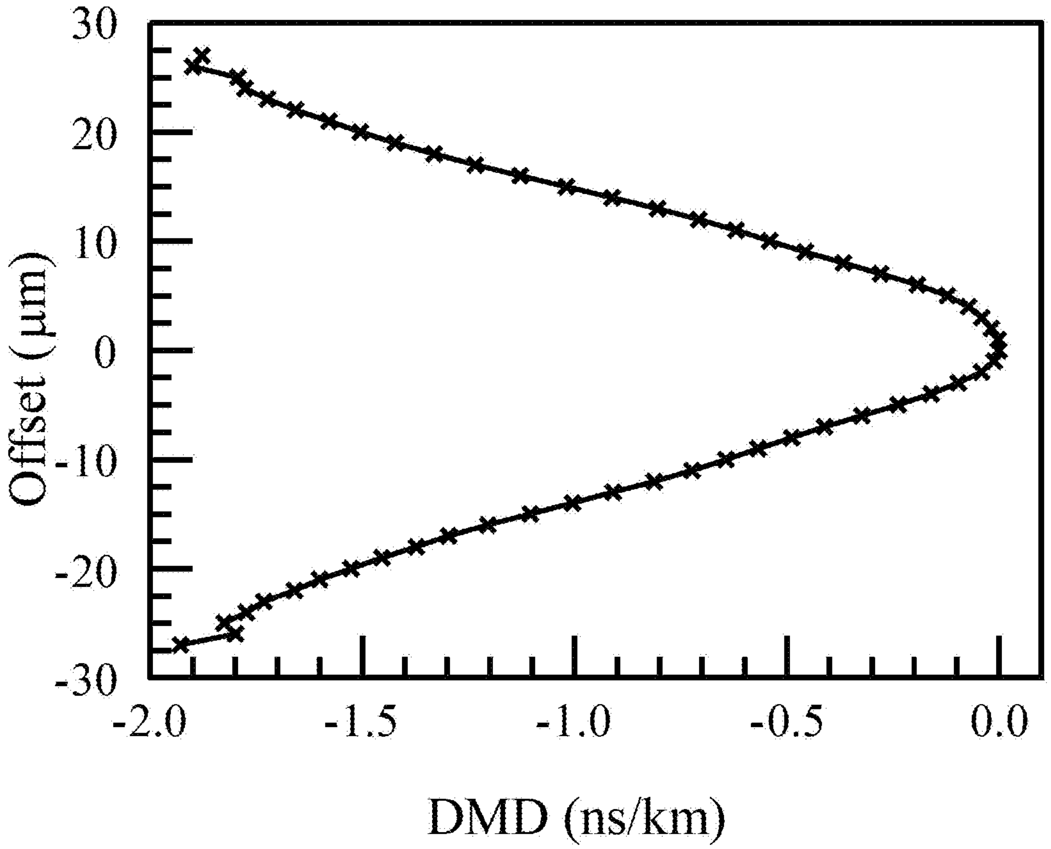


FIG. 11

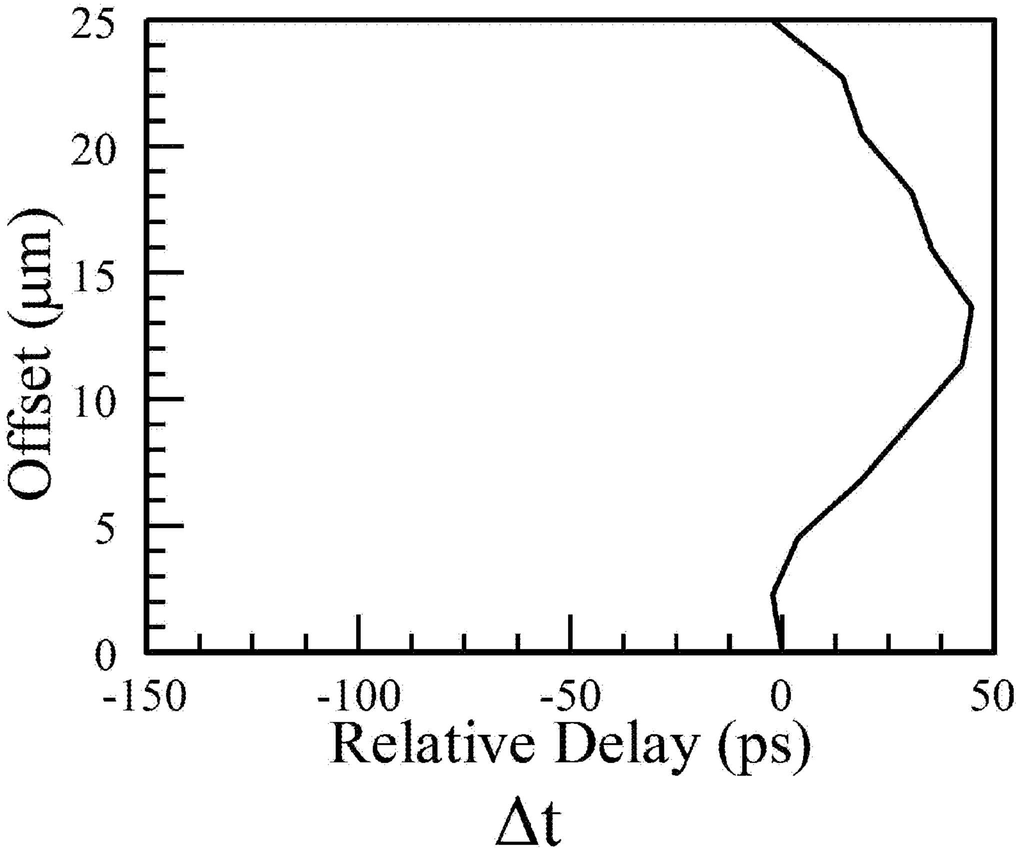


FIG. 12

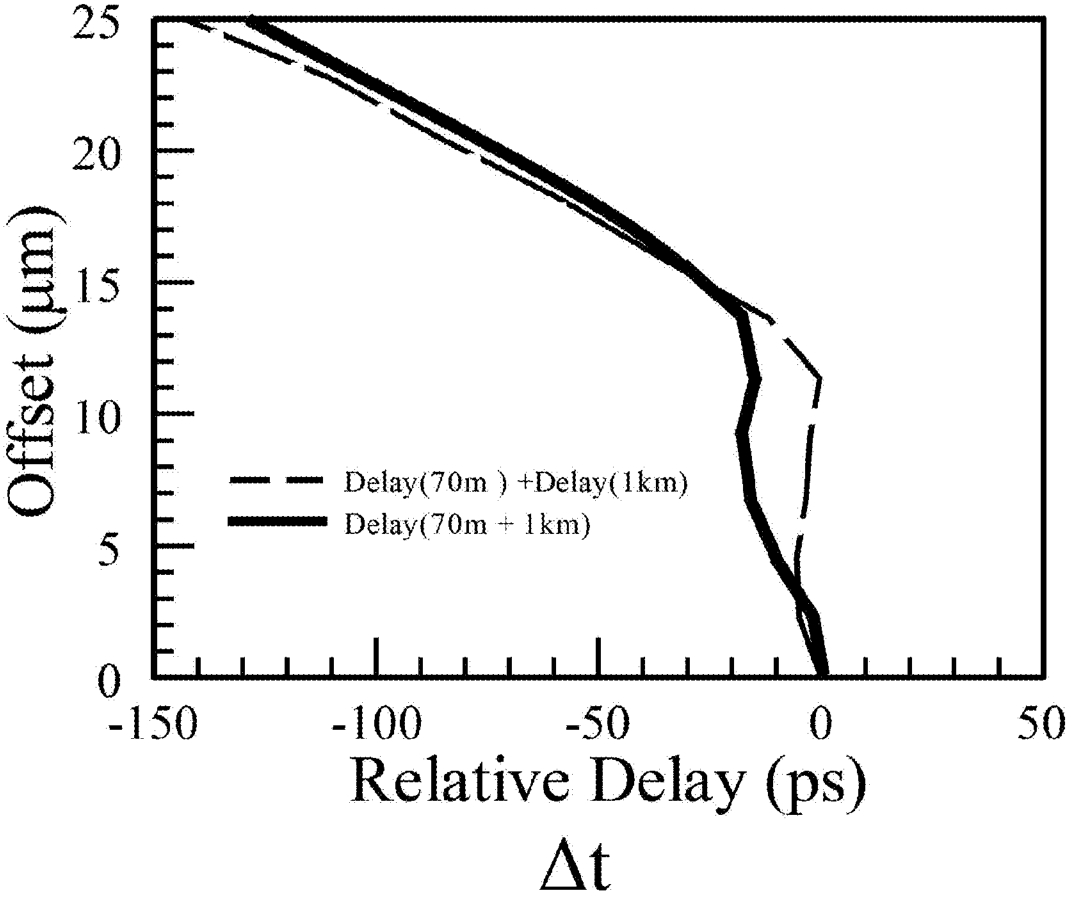

25
20
15
10
5
0
Offset (µm)
-150
-100
-50
0
50
Relative Delay (ps)
Δt
Delay(70m) +Delay(1km)
Delay(70m + 1km)

FIG. 13

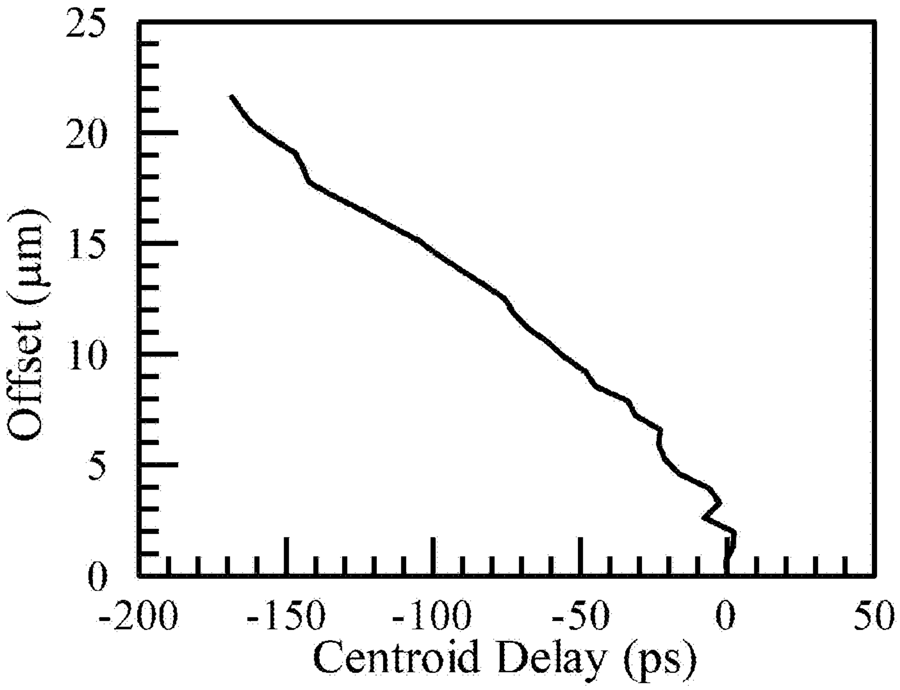


FIG. 14A

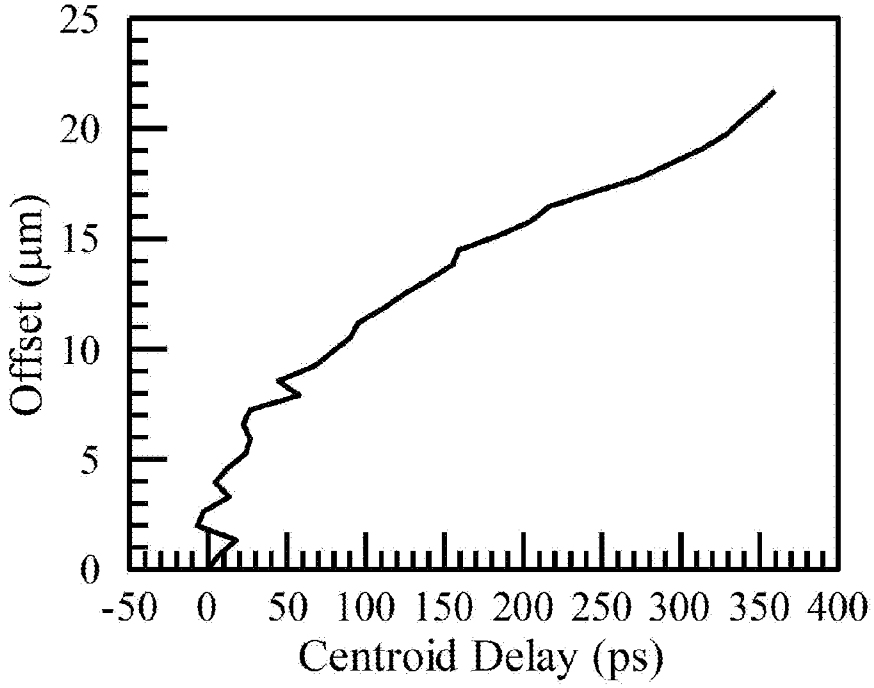
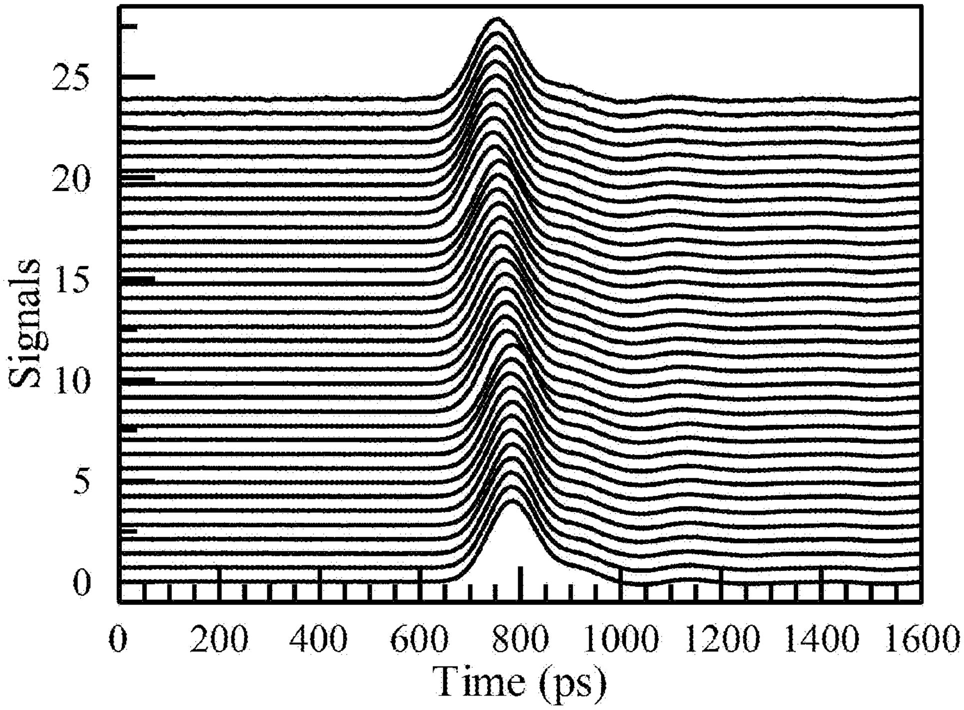


FIG. 14B



Signals
0
5
10
15
20
25
0
200
400
600
800
1000
1200
1400
1600
Time (ps)

FIG. 15

OPTICAL FIBER LINK WITH PRIMARY AND COMPENSATING OPTICAL FIBERS

[0001] This application claims the benefit of priority under 35 U.S.C. §119 of U.S. Provisional Application Ser. No. 61/881,169 filed on Sep. 23, 2013 the content of which is relied upon and incorporated herein by reference in its entirety.

FIELD

[0002] The present specification relates generally to optical fibers and more specifically to multimode optical fiber links that employ a primary optical fiber and a compensating optical fiber that provide for improved optical transmission performance over the link as compared to either the primary fiber or compensating fiber taken alone.

[0003] All references cited herein are incorporated by reference in their entirety herein.

BACKGROUND

[0004] Optical fibers are currently used to transmit optical signals. Optical fibers, including multimode optical fibers, are frequently used for data transmission or high-speed data transmission over distances ranging from a meter or less up to the distance needed to transmit throughout a building or between buildings near one another that are optical signals associated with local networks.

[0005] Multimode fibers, by definition, are designed to support multiple guided modes at a given wavelength. The bandwidth of a multimode fiber is defined by the fiber's ability to carry the different optical (guided) modes with little or no temporal separation as they travel down the fiber. This requires that the group velocities of the different optical modes be as close to the same value as possible. That is to say, there should be minimal intermodal dispersion (i.e., the difference in the group velocity between the different guided modes should be minimized) at the design ("peak") wavelength λ_P.

[0006] A multimode optical fiber can be designed to minimize the amount of intermodal dispersion and differential delays between mode groups. This is done by providing the core of the multimode fiber with a gradient-refractive-index profile whose shape is generally parabolic. The gradient-index profile is optimized for reducing intermodal dispersion when the additional distance traveled by higher-order modes is compensated for by those modes seeing a lower refractive index than lower-order modes that have to travel a shorter distance, the result being that all modes travel substantially the same overall optical path. Here, optical path means the physical distance traveled multiplied by the index of refraction of the material through which the light travels.

[0007] This minimization of intramodal dispersion becomes complicated when the light source used to send light down the multimode fiber is not strictly monochromatic. For example, a vertical-cavity, surface-emitting laser (VCSEL) has a wide-spectrum discrete emission. The VCSELs used for high-speed data transmission applications are generally longitudinally, but not transversally, single mode. As it turns out, each transverse mode of a VCSEL has its own wavelength corresponding to the various peaks of the emission spectrum, with the shorter wavelengths corresponding to the higher-order modes. Accordingly, a multimode fiber that is optimized to have a maximum bandwidth for a given wavelength will not exhibit optimum bandwidth performance when the light source causes the different modes to have different wavelengths.

[0008] Variations in the intramodal dispersion can also occur when the peak wavelength λ_P of the multimode fiber does not coincide with the operating wavelength, λ_O. For example, small errors in the curvature (alpha) of the core can result in λ_P values that are lower or higher than the target value, and this results in lower bandwidth due to variations in the optical path lengths for the different propagating mode groups. This situation can also arise when signals at more than one wavelength propagate in the multimode fiber, for example with coarse wavelength division multiplexing (CWDM). Signals propagating at lower or higher wavelengths than λ_P will incur larger differential delays than desirable, thereby decreasing the bandwidth and degrading the system performance.

[0009] One solution to the problem is to form the multimode fiber with a refractive-index profile that provides an optimized bandwidth for a light source having a particular transverse polychromatic mode spectrum rather than a single wavelength. Such an approach is described in U.S. Pat. No. 7,995,888 (hereinafter, the '888 patent). This approach makes sense under the assumption that light sources such as VCSELs all have generally identical wavelength spectra. However, the polychromatic mode spectra for VCSELs can differ substantially between the same types of VCSELs, as well as between different types of VCSELs. This means that a different optimized multimode optical fiber would have to be designed to match each of the different possible polychromatic mode spectra for VCSELs used in telecommunications applications. This approach is inefficient, and from a commercial telecommunications viewpoint is impractical and expensive to implement.

SUMMARY

[0010] An optical fiber link that utilizes concatenated primary and compensating multimode optical fibers is disclosed. The primary optical fiber has a first relative refractive index profile with a first alpha value α_{40} of about 2.1 that provides for a minimum amount of intermodal dispersion of guided modes at a peak wavelength λ_{P40} in the range from 840 nm to 860 nm, and has a first bandwidth BW_{40} of 2 GHz·km or greater. The compensating optical fiber has a second relative refractive index profile with a second alpha value α_{60}, and wherein $-0.9 \leq (\alpha_{60} - \alpha_{40}) \leq -0.1$, and a second bandwidth BW_{60} at second peak wavelength λ_{P60} greater than 880 nm. The optical fiber link has improved bandwidth and data rates for first and second optical signals within first and second wavelength ranges, respectively.

[0011] Additional features and advantages are to be set forth in the detailed description that follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the embodiments as described herein, including the detailed description that follows, the claims and the appended drawings.

[0012] It is to be understood that both the foregoing general description and the following detailed description are merely exemplary, and are intended to provide an overview or framework for understanding the nature and character of the claims. The accompanying drawings are included to provide a further understanding, and are incorporated into and constitute a part of this specification. The drawings illustrate one or more embodiment(s), and together with the description serve to explain the principles and operation of the various embodiments.

[0013] The claims as set forth below are incorporated into and constitute part of the Detailed Description as set forth below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIGS. **1**A and **1**B are a schematic diagrams of example multimode optical fiber systems that utilize the optical fiber link according to the disclosure;

[0015] FIG. **2** is an example wavelength spectrum of a VCSEL showing how the different transverse modes have different wavelengths;

[0016] FIGS. **3**A and **3**B are example cross-sectional views of the primary and compensating multimode optical fibers of the systems of FIGS. **1**A and **1**B;

[0017] FIG. **3**C is similar to FIG. **3**B and illustrates an example embodiment of a bend-insensitive compensating fiber;

[0018] FIG. **4** is a plot of wavelength (nm) vs. signal intensity (dB) that represents the measured spectrum for a 40 Gb/s VCSEL operating at a current of 8 mA;

[0019] FIG. **5** is a schematic diagram of an example measurement system for measuring the spectral characteristics of a VCSEL light source using a fiber-offset method to calculate a center-wavelength difference $\Delta\lambda_{max-c}$;

[0020] FIG. **6** is a plot of wavelength (nm) vs. fiber offset (μm) and shows the normalized wavelength spectra associated with a number of different fiber offsets as measured using the measurement system of FIG. **5**;

[0021] FIG. **7** is a plot of radial offset position (μm) vs. center wavelength (nm) for the data of FIG. **6**, which provides a measure of the center-wavelength difference $\Delta\lambda_{max-c}$;

[0022] FIG. **8** is a plot of mode group number vs. relative delay $\Delta\tau$(ns/km) for an example optical fiber having four different values of alpha detuning values $\Delta\alpha$, namely $\Delta\alpha=0$, $\Delta\alpha=-0.1$, $\Delta\alpha=-0.2$ and $\Delta\alpha=-0.3$;

[0023] FIG. **9** is a plot of relative refractive index profile Δ(%) vs. radius r for an example bend-insensitive compensating fiber;

[0024] FIG. **10** is a plot of mode group number vs. relative delay (ns/km) for the compensating fiber set forth in Table 5 (below) for an operating wavelength of 850 nm;

[0025] FIG. **11** is a plot of differential (relative) delay (DMD; ns/km) vs. radial launch offset (μm) for an example compensating fiber with $\alpha_{60}\approx 1.88$ for fiber scaled to 1,000 m in length;

[0026] FIG. **12** is a plot of relative delay Δt (ps) vs. radial launch offset (μm) for an example primary fiber with L1=1 km and an example compensating fiber with L2=70 m;

[0027] FIG. **13** is a plot similar to that of FIG. **12** for concatenated primary and compensating fibers;

[0028] FIGS. **14**A and **14**B are plots similar to that of FIG. **12** for example OM4 fibers that have left-tilt (FIG. **14**A) and right-tilt (FIG. **14**B) for the centroid delay;

[0029] FIG. **15** is a plot of the signal strength (relative units) versus time, and indicates that the DMD of the example optical fiber link formed based on the tilt characteristics of FIGS. **14**A and **14**B is flat but has slight left tilt at 1042 nm.

DETAILED DESCRIPTION

[0030] The symbol μm and the word "micron" are used interchangeably herein.

[0031] The term "relative refractive index," as used herein, is defined as:

$$\Delta(r)=[n(r)^2-n_{REF}^2)]/2n(r)^2,$$

[0032] where n(r) is the refractive index at radius r, unless otherwise specified. The relative refractive index is defined at the fiber's peak wavelength λ_P. In one aspect, the reference index n_{REF} is silica glass. In another aspect, n_{REF} is the maximum refractive index of the cladding. As used herein, the relative refractive index is represented by Δ and its values are given in units of "%," unless otherwise specified. In cases where the refractive index of a region is less than the reference index n_{REF}, the relative refractive index is negative and is referred to as having a depressed region or depressed index, and the minimum relative refractive index is calculated at the point at which the relative index is most negative, unless otherwise specified. In cases where the refractive index of a region is greater than the reference index n_{REF}, the relative refractive index is positive and the region can be said to be raised or to have a positive index.

[0033] The parameter α (also called the "profile parameter" or "alpha parameter") as used herein relates to the relative refractive index Δ, which is in units of "%," where r is the radius (radial coordinate), and which is defined by:

$$\Delta(r)=\Delta_0\left[1-\left(\frac{r-r_m}{r_0-r_m}\right)^{\alpha}\right],$$

[0034] where r_m is the point where Δ(r) is the maximum Δ_0 (also referred to in certain cases below as Δ_{1MAX}), r_0 is the point at which Δ(r)% is zero and r is in the range $r_i \le r \le r_f$, where Δ(r) is defined above, r_i is the initial point of the α-profile, r_f is the final point of the α-profile and a is an exponent that is a real number. For a step index profile, $\alpha>10$, and for a gradient-index profile, $\alpha<5$. It is noted here that different forms for the core radius r_0 and maximum relative refractive index Δ_0 can be used without affecting the fundamental definition of Δ. The maximum relative refractive index Δ_0 is also called the "core delta," and these terms are used interchangeably herein. For a practical fiber, even when the target profile is an alpha profile, some level of deviation from the ideal situation can occur. Therefore, the alpha value for a practical fiber is the best-fit alpha from the measured index profile.

[0035] The limits on any ranges cited herein are considered to be inclusive and thus to lie within the range, unless otherwise specified.

[0036] The NA of an optical fiber means the numerical aperture as measured using the method set forth in IEC-60793-1-43 (TIA SP3-2839-URV2 FOTP-177) titled "Measurement Methods and Test Procedures: Numerical Aperture".

[0037] The term "dopant" as used herein refers to a substance that changes the relative refractive index of glass relative to pure undoped SiO_2. One or more other substances that are not dopants may be present in a region of an optical fiber (e.g., the core) having a positive relative refractive index Δ.

[0038] The term "mode" is short for a guided mode or optical mode. A multimode optical fiber means an optical fiber designed to support the fundamental guided mode and at least one higher-order guided mode over a substantial length of the optical fiber, such as 2 meters or longer.

[0039] The cutoff wavelength λ_C of a mode is the minimum wavelength beyond which a mode ceases to propagate in the optical fiber. The cutoff wavelength of a single-mode fiber is the minimum wavelength at which an optical fiber will support only one propagating mode, i.e., below the cutoff wavelength, two or more modes can propagate. Typically the highest cutoff wavelength λ_C of a multimode optical fiber corresponds to the cutoff wavelength of the LP_{11} mode. A mathematical definition can be found in Jeunhomme's *Single Mode Fiber Optics* (New York: Marcel Dekker, 1990; pp. 39-44), wherein the theoretical fiber cutoff is described as the wavelength at which the mode propagation constant becomes equal to the plane wave propagation constant in the outer cladding. A measured cutoff wavelength λ_C is normally lower than the theoretical cutoff wavelength, typically 20 nm to 50 nm lower for a 2 meter fiber with substantially straight deployment.

[0040] The operating wavelength λ_O is the wavelength at the particular system operates, with λ_O=850 nm being an example of an operating wavelength used in multimode telecommunications systems that utilize VCSELs as the light source, and that may be used herein. In systems where CWDM is employed there may be more than one operating wavelength, for example λ_{O1}, λ_{O2}, λ_{O3}, and λ_{O4}. The "peak"-wavelength λ_P is the wavelength at which a particular optical fiber has the highest bandwidth. The operating wavelength is the wavelength at which the fiber is operating and is not necessarily the peak wavelength. For example a multimode fiber can have a peak wavelength λ_P=850 nm but the light traveling therein can have an operating wavelength of 852 nm.

[0041] In systems transmitting at a single wavelength, the optimum value of λ_P may be equal to the operating wavelength, for example, $\lambda_P=\lambda_O$=850 nm or $\lambda_P=\lambda_O$=1310 nm. In systems transmitting at more than one wavelength, the optimum value of λ_P may be located near the center of the range of operating wavelengths, for example $\lambda_{O1}<\lambda_{O2}<\lambda_P<\lambda_{O3}<\lambda_{O1}$, where for example 800 nm$<\lambda_P<$900 nm, or 900 nm$<\lambda_P<$1100 nm, or 1200 nm$<\lambda<$1400 nm or 1500 nm$<\lambda_P<$1600 nm. The peak wavelengths of primary and compensating optical fibers **40** and **60** are denoted as λ_{P40} and λ_{P60}, respectively, where appropriate.

[0042] The wavelength λ_{01} is the wavelength of the LP_{01} mode as generated by a VCSEL light source and is generally the longest (highest) wavelength of a VCSEL wavelength spectrum. In certain cases below, the wavelength λ_{01} is the same as the peak wavelength λ_P.

[0043] The VCSEL wavelength bandwidth $\Delta\lambda_{max}$ is a measure of the wavelength difference between the lowest-order and highest-order transverse modes.

[0044] The center operating wavelength λ_{CW} is used in connection with a VCSEL light source and is the center wavelength of the particular VCSEL spectrum. It is noted that as the VCSEL spectrum typically varies as a function of radius, the center operating wavelength also varies as a function of the VCSEL radius. The difference in the center operating wavelengths for different VCSEL spectra associated with different radial positions is defined by the maximum center-wavelength difference $\Delta\lambda_{max-c}$ and can be measured using the fiber-offset method as described below in connection with measurement system **100** of FIG. **5**.

[0045] The overfill bandwidth (BW) of an optical fiber is defined herein as using overfilled launch conditions at 850 nm according to IEC 60793-1-41 (TIA-FOTP-204), Measurement Methods and Test Procedures: Bandwidth. The minimum calculated effective modal bandwidths can be obtained from measured differential mode delay spectra as specified by IEC 60793-1-49 (TIA/EIA-455-220), Measurement Methods and Test Procedures: Differential Mode Delay. The units of bandwidth for an optical fiber can be expressed in MHz·km, GHz·km, etc., and bandwidth expressed in these kinds of units is also referred to in the art as the bandwidth-distance product. The bandwidth here is also called modal bandwidth, which is defined in part by modal dispersion. At the system level, the overall bandwidth can be limited by chromatic dispersion, which limits the system performance at a high bit rate.

[0046] The term "modal dispersion" or "intermodal dispersion" is, in an optical fiber, a measure of the difference in the travel times of the different modes of an optical fiber for light of a single wavelength and is primarily a function of the alpha profile of the optical fiber.

[0047] The term "modal delay" is used to denote for laser pulses the time delay of the different modes due to modal dispersion and refers to the greatest delay between the different modes, unless stated otherwise.

[0048] The term "material chromatic dispersion" or "material dispersion" is a measure of how strongly a material causes light of different wavelengths to travel at different speeds within the material, and as used herein is measured in units of ps/(nm·km).

[0049] The term "chromatic modal dispersion" is related to both material chromatic dispersion and modal dispersion and is a measure of the difference in the travel times of different modes of an optical fiber when these modes have different wavelengths. In multimode fibers, the chromatic dispersion for each mode is approximately the same as the material dispersion.

[0050] The term "compensation," as used in connection with the modal delay of the compensating multimode optical fiber that compensates the chromatic modal dispersion of the primary multimode optical fiber, means either partial or complete compensation, i.e., a reduction or elimination of the adverse effects of the chromatic modal dispersion on performance such as bandwidth.

Multimode Optical Fiber System

[0051] FIG. **1A** is a schematic diagram of an example multimode optical fiber system ("system") **10** that includes an optical transmitter **20**, first and second multimode optical fibers **40** and **60** that define an optical link **70** of length LT, and a receiver **80**. The optical transmitter **20** has a light source **24**. In an example, light source **24** is a VCSEL operating at a wavelength λ_O of about 850 nm that generates an output (e.g., light or optical signals) **26** at a number of transverse modes that have different wavelengths, with the lowest-order transverse mode LP_{01} having a wavelength λ_{01}, which in an example is 850 nm, while the other higher-order modes (LP_{11}, LP_{21}, LP_{02}, etc.) have shorter wavelengths, as illustrated in the example VCSEL spectrum of FIG. 2 taken from the '888 patent, wherein $\Delta\lambda_{max}\approx$1.5 nm. In another example, light source **24** is a VCSEL operating at a wavelength λ_O longer than 850 nm, for example about 900 nm, 980 nm, 1060 nm, 1310 nm or 1550 nm. In another example, light source **24** is a Silicon-photonics laser that generates an output **26** at a single wavelength, λ_O around 1310 nm In another example, light source **24** can generate optical signals **26** at first and second wavelengths.

[0052] In another example, light source **24** is an array of a Silicon-photonics laser operating at different wavelengths, $<\lambda_{O1}$, $<\lambda_{O2}$, $<\lambda_{O3}$, and $<\lambda_{O4}$, and multiplexed together into a single output **26**. The optical transmitter **20** is configured to drive light source **24** so that light **26** carries information as optical signals. As a VCSEL is used herein as the exemplary light source **24**, the VCSEL is also referred to herein as VCSEL **24**.

[0053] FIG. **1**B is similar to FIG. **1**A and illustrates an example system **10** wherein the transmitter and receiver are combined to form transceivers **21** that are optically connected by optical fiber link **70**. Transceivers **21** can both transmit and receive optical signals **26**. In an example, transceivers can transmit and receive optical signals **26** having different wavelengths.

[0054] The first multimode optical fiber **40** have first and second ends **42** and **44** that define a length L1, with the first end being optically coupled to light source **24**. The first multimode optical fiber **40** is a standard type of multimode optical fiber having a peak wavelength of λ_{P40} that can be, for example, 850 nm, which matches the wavelength λ_{01} of the lowest-order mode of light source **24**. The first multimode optical fiber **40** is "standard" in the sense that it has an alpha profile (i.e., a value for α) that generally minimizes the intermodal dispersion at the peak wavelength of λ_{P40}.

[0055] In an example, first multimode optical fiber **40** carries greater than about 50 LP modes and has a peak wavelength λ_{P40} of 850 nm, 980 nm or 1,060 nm, 1310 nm or 1550 nm. The first multimode optical fiber **40** is the primary optical fiber in system **10** and so is referred to hereinafter as "primary fiber **40**." Likewise, second multimode optical fiber **60** is a compensating optical fiber designed to compensate for chromatic modal dispersion arising in primary fiber **40** and so is referred to hereinafter as "compensating fiber **60**."

[0056] In practice, the order of the primary and compensating fibers can be switched so that the compensating fiber **60** is directly connected to transmitter **20** and the primary fiber **40** is directly connected to the receiver **80**.

[0057] In an example embodiment, primary fiber **40** is optimized to transmit an optical signal over distances from about tens of meters to several hundred meters with low modal delay. The primary fiber **40** can be used in system **10** to distribute an optical signal throughout a building or a limited area, in accord with current practices for multimode optical fibers. The primary fiber **40** may also be intended for high data-rate transmission, such as transmission speeds of greater than 10 Gb/s, greater than 20 Gb/s, greater than 25 Gb/s or greater than 40 Gb/s.

[0058] Examples of primary fiber **40** include an OM3-type fiber that has a nominal bandwidth BW_{40}=2.0 GHz·km or better (higher) at 850 nm, and OM4-type fiber that has a nominal bandwidth BW_{40}=4.7 GHz·km or better at 850 nm. In another example, primary fiber **40** has a nominal bandwidth of BW_{40} of 2 GHz·km or better over a first wavelength range from 840 nm to 860 nm.

[0059] Other examples of primary fiber **40** include multimode fiber optimized for longer wavelengths than 850 nm. In one example, primary fiber **40** is optimized to have a bandwidth greater than 2.5 GHz·km at a wavelength situated in the 900 nm to 1250 nm range. In a preferred embodiments, primary fiber **40** exhibits an overfilled bandwidth at a wavelength situated in the 900 nm to 1100 nm range, which is greater than 4 GHz·km. In another example, primary fiber **40** is optimized to have a bandwidth greater than 2.5 GHz·km at a wavelength situated in the range from 1260 nm to 1610 nm. In an example embodiment, primary fiber **40** exhibits an overfilled bandwidth at 1310 nm which is greater than 3.75 GHz·km. In another embodiment, primary fiber **40** exhibits an overfilled bandwidth at 1550 nm which is greater than 3.75 GHz·km. An example primary fiber has an alpha α_{40} of about 2.1, e.g., in the range from 2.0 to 2.2.

[0060] The compensating fiber **60** has first and second ends **62** and **64** that define a length L2, with the first end being optically coupled to second end **44** of primary fiber **40** at a coupling location **52** to define optical fiber link **70**. The particular configuration and properties of compensating fiber **60** are described in greater detail below. The second end **64** of compensating fiber **60** is optically coupled to receiver **80**, which includes a detector **84** such as a photodetector.

[0061] FIGS. **3**A and **3**B are respective cross-sectional views of primary and compensating fibers **40** and **60**. The primary fiber **40** has a core **46** with a radius r_0 and a surrounding cladding **48**. The compensating fiber **60** has a core **66** with a radius r_1 and a surrounding cladding **68**. In an example, radius r_0 is equal to or substantially equal to radius r_1 for the purpose of optimizing the optical coupling between fibers **40** and **60** at coupling location **52**. In an example, coupling location **52** is defined by a splice between the two optical fibers **40** and **60**, or by an optical fiber connector. At least one of primary fiber **40** and compensating fiber **60** can have a low index trench in the cladding for the purpose of improving fiber-bending performance.

[0062] FIG. **3**C is similar to FIG. **3**B and illustrates an example embodiment of a bend-insensitive compensating fiber **60**. In an example, the bend insensitive property of compensating fiber **60** is provided by the addition of a fluorine doped trench **67** (i.e., a low-index ring) in the cladding region adjacent core **66**. The trench **67** need not be immediately adjacent core **66**. Examples of such a bend-insensitive fiber are disclosed in U.S. Pat. No. 7,680,381. It will be understood that the term "bend-insensitive" and like terms actually mean "substantially bend insensitive."

[0063] As it turns out, the spectra from different VCSELs can differ substantially. For typical 10 Gb/s VCSELs, the wavelength bandwidth $\Delta\lambda_{max}$ is about 1 nm. But for VCSELs used in parallel optics and for higher data rates of 25 Gb/s and 40 Gb/s, the wavelength bandwidth $\Delta\lambda_{max}$ can be 2 nm to 3 nm or even greater. FIG. **4** is a plot of wavelength (nm) vs. signal intensity (dB) that represents the measured spectrum for a 40 Gb/s VCSEL operating at a current of 8 mA. The spectrum of FIG. **4** shows the discrete transverse modes and also indicates that the the bandwidth $\Delta\lambda_{max}$ of the VCSEL spectrum exceeds 4 nm.

[0064] In addition, the VCSELs available on the market and that are compliant with the relevant standard can have output wavelengths that range from 840 nm to 860 nm. This means that a given VCSEL light source **24** can operate relatively far off of the peak wavelength λ_P for a standard multimode optical fiber such as primary fiber **40**. It is therefore difficult and impractical to produce many different multimode fibers that are optimized for all the possible wavelength spectra for a given type of VCSEL light source **24**.

[0065] As discussed above and illustrated in FIGS. **2** and **4**, VCSELs have discrete transverse modes having different wavelengths. The modes are generally denoted as LP_{XX}, in a similar way to the multiple modes supported by multimode fibers. The LP_{01} mode is the fundamental (lowest-order) and is located at the center of the VCSEL axis, while the higher-order modes are located increasingly farther away from the VCSEL axis and have increasingly shorter wavelengths.

[0066] The RMS spectral width can be used to characterize the VCSEL linewidth. For a 10 Gb/s Ethernet transmission by a VCSEL, the RMS linewidth of the VCSEL is less than or equal to about 0.45 nm. For 40 Gb/s and 100 Gb/s parallel optics transmission, the RMS linewidth of the VCSEL is generally less than or equal to about 0.65 nm.

[0067] Thus, when VCSEL light source **24** is optically coupled to primary fiber **40**, the lower-order mode with the largest wavelength travels over an optical path that runs down the center of the fiber, while the higher-order modes that have smaller wavelengths travel over optical paths that are farther away from the center of the fiber. The spatial wavelength dependence of light **26** coupled into primary fiber **40**, as judged by the optical spectrum as a function of the radial position, depends on the particular VCSEL spectral characteristics and the optics used to couple the light from the VCSEL into the primary fiber. The radial wavelength property of the VCSEL light **26** launched into primary fiber **40** can be measured.

[0068] FIG. **5** is a schematic diagram of an example measurement system **100** used to measure the radial wavelength dependence of VCSEL **24**. The measurement system **100** includes a pattern generator **106** is used to electrically drive VCSEL **24** as packaged in an SFP+ or XFP form-factor transmitter **110**. A multimode fiber—say, fiber **40**—is directly connected at one end to VCSEL **24** and has a connector **45** at its opposite end. A single mode fiber **120** is also provided that has a connector **125** at one end and has its opposite end optically connected to an optical spectrum analyzer **140**. The connectors **45** and **125** are operably supported in a precision alignment stage **150** that is used to optically couple fibers **40** and **120** and to provide select radial offsets between the two fibers ("fiber offsets").

[0069] The light **26** from VCSEL **24** is transmitted through fibers **40** and **120** for each fiber offset, as set by precision alignment stage **150**. This transmitted light **26** is received by optical spectrum analyzer **140**, which provides an optical spectrum for each fiber offset. Thus, offset single-mode fiber **120** is used to detect light **26** traveling in different radial positions in primary fiber **40**.

[0070] FIG. **6** is a plot of wavelength (nm) vs. fiber offset (μm) and shows the normalized wavelength spectra associated with a number of different fiber offsets. A commercially available transmitter **110** was used to generate light **26**. The height of each trace is normalized to 2.5 for the maximum height of the spectrum obtained with zero fiber offset. The offset for all other traces (spectra) was added in increments of 3.125 microns. The traces in FIG. **6** show that at each fiber offset there are several spectral peaks associated with the different VCSEL modes. However, the strength of each VCSEL mode varies with the fiber offset.

[0071] The center operating wavelength λ_{CW} for each fiber offset can be calculated by one of the following equations.

$$\lambda_{CW}=\int S(\lambda)\cdot\lambda\cdot d\lambda/\int S(\lambda)\cdot d\lambda$$

$$\lambda_{CW}=\sqrt{\int S(\lambda)\cdot\lambda^2\cdot d\lambda/\int S(\lambda)\cdot d\lambda}$$

[0072] These two equations produce essentially the same center results of center wavelength λ_{CW} to within 0.002 nm or less. For the traces in FIG. **6**, the center wavelength λ_{CW} at each offset is calculated and plotted in FIG. **7**. The plot of FIG. **7** indicates that the center wavelength λ_{CW} drops as a function of greater fiber offset, with a maximum difference of 0.25 nm. For different VCSELs, the plot of FIG. **7** will vary in detail, but the general trend of center wavelength λ_{CW} getting smaller as the fiber offset increases will be present.

[0073] The plot of FIG. **7** shows a center-wavelength difference of:

$$\Delta\lambda_{max\text{-}c}\approx(850.92-850.67)\approx 0.25\text{ nm.}$$

[0074] The value of $\Delta\lambda_{max\text{-}c}$ can be as high as about 1 nm (see, e.g., Pimpinella et al., "Investigation of bandwidth dependence on chromatic and modal dispersion in MMF links using VCSELs," *OFC/NFOEC Technical Digest* (January 2012), wherein $\Delta\lambda_{max\text{-}c}\approx 0.9$ nm).

[0075] Because the average/effective wavelength of VCSEL **24** varies with the radial position, the excited modes in primary fiber **40** carry different wavelengths. Due to the material chromatic dispersion, the modal delay of fiber **40** is optimized for one wavelength only. Therefore, the difference in the wavelengths of light **26** launched into the different modes, which are spatially located at different radial positions, causes an additional time-delay difference between the different modes when reaching end **44** of primary fiber **40**.

[0076] Thus, while primary fiber **40** has optimized modal dispersion (i.e., minimum modal delay), there is now chromatic modal dispersion that is related to both the VCSEL wavelength distribution and the fiber material dispersion. Multimode fibers with a peak wavelength λ_P=850 nm typically use GeO_2 to define the alpha profile of the fiber. However, this material has a relatively high chromatic dispersion, and therefore the chromatic modal dispersion will have a significant impact on a fiber optical transmission system that utilizes VCSEL **24** and multimode fiber **40**.

[0077] As a first order approximation in estimating the time delay that derives from the chromatic modal dispersion in a multimode fiber, one can assume that the wavelength scales linearly with the radial position. This assumption yields four key parameters that can be used to estimate the time delay owing to chromatic dispersion:

[0078] the chromatic dispersion value D of the multimode fiber at the peak wavelength;

[0079] the value of $\Delta\lambda_{max\text{-}c}$, i.e., the maximum center-wavelength difference of light source **24** as measured, for example, via the center wavelength λ_{CW} as a function of radial offset using measurement system **100**;

[0080] the difference in the alpha parameter between the fiber's actual value α_a and the optimum value α_{opt}, i.e., $\Delta\alpha=\alpha_a-\alpha_{opt}$, which in the discussion below is also defined, between the primary and compensating fibers, as

$$\Delta\alpha=\alpha_{60}-\alpha_{40}\text{; and}$$

[0081] the difference in the optimum operating wavelength λ_P and the wavelength λ emitted by VCSEL **24**.

[0082] The maximum time-delay difference Δt due to chromatic modal dispersion that arises in primary fiber **40** can be estimated by the following equation, where D is the amount of chromatic dispersion (typically between −80 and −120 ps/(nm·km) at a wavelength of about 850 nm, with −100 ps/(nm·km) being representative of most multimode fibers, and L1 is the length of the primary fiber:

$$\Delta t=\Delta\lambda_{max\text{-}c}\cdot D\cdot L1 \qquad (1)$$

[0083] To at least partially compensate for the time delay caused by chromatic modal dispersion in fiber **40**, compensating fiber **60** is configured to provide an opposite modal delay, i.e., an opposite time delay for the various guided modes. In other words, the maximum compensating modal delay of compensating fiber **60** has the opposite sign to that of the chromatic modal dispersion of primary fiber **40**, and has a magnitude sufficient to at least partially (and in an example, completely) cancel the delay due to chromatic modal dispersion. This is used to reduce or eliminate the overall time delay in the concatenated primary and secondary fibers **40** and **60** of system **10**.

[0084] To achieve this compensating effect, compensating fiber **60** is provided with a modal delay by detuning its alpha value. In particular, the alpha value of compensating fiber **60** is detuned from its otherwise optimum value at the peak wavelength λ_{P40} for primary fiber **40**, i.e., $\alpha_{40}>\alpha_{60}$, so that the compensating fiber has a relatively high modal delay.

[0085] FIG. **8** is a plot of mode group number vs. relative delay $\Delta\tau$ (ns/km) for an example fiber having four different alpha detuning values $\Delta\alpha$, namely, $\Delta\alpha=0$, $\Delta\alpha=-0.1$, $\Delta\alpha=-0.2$ and $\Delta\alpha=-0.3$. One example of compensating fiber **60** has a maximum relative refractive index $\Delta_0=1\%$, and the core radius $r_1=r_0=25$ μm, so that the NA and core size match those of a standard 50 μm, multimode primary fiber **40**.

[0086] It can be found that the maximum relative delay $\Delta\tau_{max}$ is related to the $\Delta\alpha$ (relative to the optimum α at 850 nm) by a simple equation, namely:

$$\Delta\tau_{max}=10\cdot\Delta_0\cdot\Delta\alpha(\text{ns/km}) \tag{2A}$$

[0087] When $\Delta=1\%$, this reduces to:

$$\Delta\tau_{max}=10\cdot\Delta\alpha(\text{ns/km}) \tag{2B}$$

[0088] When $\Delta=0.5\%$, equation 2A reduces to:

$$\Delta\tau_{max}=5\cdot\Delta\alpha(\text{ns/km}) \tag{2C}$$

[0089] In system **10**, the modal delay imparted to compensating fiber **60** by its detuned alpha parameter α_{60} compensates at least in part for the modal delays generated in primary fiber **40** from chromatic modal dispersion due to using VCSEL **24** having a polychromatic wavelength spectrum. Consequently, compensating fiber **60** has a relatively small bandwidth as compared to primary fiber **40** having a peak wavelength λ_{P40}, and in fact would not be suitable for use as a transmission (primary) optical fiber in system **10**. An example bandwidth BW_{60} at λ_{P40} for compensating fiber **60** is $BW_{60}<500$ MHz·km, while in another example $BW_{60}<300$ MHz·km, and in another example $BW_{60}<100$ MHz·km.

[0090] Another way of appreciating how much smaller the bandwidth BW_{60} for compensating fiber **60** is as compared to the bandwidth BW_{40} of primary fiber **40** is to consider the ratio R_{BW} of these bandwidths at λ_{P40}. In example embodiments, the ratio $R_{BW}=BW_{40}/BW_{60}$ is $R_{BW}>3$ or $R_{BW}>5$, or $R_{BW}>10$.

[0091] However, a benefit of compensating fiber **60** having such a small bandwidth is that only a relatively small length L2 of the compensating fiber is needed to provide the requisite chromatic modal dispersion for the entire system **10**. The delays at each radial position in fiber **40** and in compensating fiber **60** are additive so that with the use of the compensating fiber, the overall delay for system **10** can be controlled as a function of radial position.

[0092] Also in an example embodiment, compensating fiber **60** is designed to have a peak wavelength λ_{P60} that differs from the peak wavelength λ_{P40} of primary fiber **40**. This is analogous to detuning the alpha parameter in compensating fiber **60**. In an example embodiment, $\lambda_{P60}-\lambda_{P40}\geq400$ nm.

[0093] In another example embodiment, compensating fiber **60** has a bandwidth BW_{60} at λ_{P60} greater than 880 nm comparable to bandwidth BW_{40} at λ_{P40}. Thus, in example embodiments, $BW_{60}\geq2$ GHz·km, or $BW_{60}\geq4$ GHz·km, or $BW_{60}\geq5$ GHz·km, or $BW_{60}\geq7$ GHz·km for the wavelength range greater than 880 nm. This allows for optical fiber link **70** to have a relatively high link bandwidth BW_L over the first and second wavelength ranges so that respective optical signals **26** within these respective wavelength ranges can be transmitted over the link at relative high data rates. In an example, fiber link **70** has a link bandwidth BW_L in the range from 2500 MHz·km to 2800 MHz·km and can transmit optical signals of 20 Gb/s or greater over the link length LT=L1+L2 for first and second optical signals **26** with respective wavelengths in the first and second wavelength ranges. In an example, the link length LT is in the range from 50 m to 800 m.

[0094] In an example, the length L2 of compensating fiber **60** is selected to optimize the overall performance of system **10**, in particular the bandwidth performance of the system. This is somewhat counterintuitive for the case where compensating fiber **60** has a small bandwidth relative to primary fiber **40**. The optimization of the bandwidth of system **10** is accomplished by providing compensating fiber **60** with the appropriate amount of alpha detuning (and thus mode delay) for the spectral characteristics of light source **24** and the particular primary fiber **40** used in system **10**.

[0095] The length L2 of fiber **60** (in meters) suitable for use in system **10** can be calculated using the following formulas based on the maximum time delay difference Δt due to chromatic dispersion and the maximum relative delay $\Delta\tau_{max}$ per unit length for compensating fiber **60**:

$$L2=|\Delta t|/(|\Delta\tau_{max}|) \tag{3A}$$

$$L2=|\Delta t|/(10\cdot|\Delta_0\cdot\Delta\alpha|) \tag{3B}$$

[0096] Equation 3B expressly shows that the greater the $\Delta\alpha$, the smaller the length L2 of fiber **60** is required to compensate for the chromatic dispersion effect in primary fiber **40**. To this end, in one embodiment, an example compensating fiber **60** has a value for $\Delta\alpha$ in the range $-0.1\leq\Delta\alpha\leq-0.9$. In another embodiment, an example compensating fiber **60** has a value for $\Delta\alpha$ in the range, $-0.06\geq\Delta\alpha\geq-0.1$. In another embodiment, an example compensating fiber **60** has a value for $\Delta\alpha$ in the range, $0.3\leq|\Delta\alpha|\leq0.8$. In another embodiment, an example compensating fiber **60** has a value for $\Delta\alpha$ in the range, $-0.3\geq\Delta\alpha\geq-0.7$. In another embodiment, an example compensating fiber **60** has a value for $\Delta\alpha$ in the range, $0.3\leq\Delta\alpha\leq0.8$.

[0097] It is noted that some amount of chromatic modal dispersion exists also in compensating fiber **60**. However, the chromatic modal dispersion is very small compared to the modal delay created by the alpha detuning and can thus be ignored for a short length L2 of compensating fiber **60**. However, this effect can be taken into account if the length L2 of compensating fiber **60** needs to be relatively large. This situation is addressed in greater detail below.

[0098] In other embodiments, compensating fiber **60** can have a non-α profile to provide additional latitude in forming the relative refractive index profile for the purpose of obtaining a select differential mode delay to match the higher order modes of the VCSEL light source **24** to obtain improved chromatic dispersion compensation. In an example, the relative refractive index profile for compensating fiber **60** includes trench **67** (see FIG. **3**C), which provides the compensating fiber with an enhanced insensitivity to bending.

[0099] In examples where $\Delta\alpha$ is large (e.g., $\Delta\alpha \leq -0.2$), the length L2 of compensating fiber **60** may be quite short, e.g., L2≤50 m or L2≤20 m, or L2≤15 m or L2≤10 m, or L2≤5 m. When compensating fiber **60** can be used in system **10** to compensate for chromatic modal dispersion effects, the overall system or link bandwidth BW_L can be made greater than either the bandwidth BW_{40} of fiber **40** or the bandwidth BW_{60} of fiber **60** alone.

[0100] It is also noted that the detuned alpha parameter α_{60} of compensating fiber **60** provides more tolerance in making the compensating fiber because the fiber can accommodate a larger refractive index profile error as compared to the design target since the compensating fiber has a shorter length than primary fiber **40**. For VCSELs **24** with different spatial wavelength dependence as characterized by different values of the center operating wavelength λ_{CW} and different values of $\Delta\lambda_{max-c}$, one can achieve optimum system performance by choosing different lengths L2 of compensating fiber **60** and without having to manufacture another type of primary fiber **40**. In example embodiments, the length ratio L1/L2 of primary fiber **40** as compared to compensating fiber **60** is 2:1 or 3:1 or 5:1 or 10:1 or 20:1 or even 50:1. In an example embodiment, L1/L2 is in the range from 2≤L1/L2≤50.

[0101] The length L2 of compensating fiber **60** can be adjusted to at least partially compensate for varying amounts of chromatic modal dispersion effects that arise in primary fiber **40** due to the different lengths L1 of the primary fiber and the different spectral characteristics of light source **24**. To this end, in an example embodiment, a number of compensating fibers **60** having the same general optical properties (i.e., $\Delta\alpha$, $\Delta\lambda_P$, core radius, etc.) can be produced in different lengths L2, such as 2 m, 5 m, 10 m, 50 m, 100 m, etc., and then used alone or in combination with each other via concatenation to provide the overall length L2 necessary to achieve a desired degree of chromatic dispersion compensation in system **10**.

Example Compensating Fibers

[0102] Table 1 below illustrates the calculation of the length L2 of compensating fibers **60** for use in several configurations for system **10**, where fibers **40** and **60** each have a relative refractive index Δ=1% and a core diameter of 50 μm. The example compensating fibers **60** in Table 1 are optimized for operation with an example light source **24** generating light at a wavelength λ_{01}=850 nm, and in Examples 6 and 7 are optimized for operation with an example light source **24** generating light at peak wavelengths of λ_{01}=980 nm and 1060 nm, respectively.

[0103] Equation 1 above was used to calculate the time delay Δt per kilometer of primary fiber **40** based on values for $\Delta\lambda_{max-c}$, D and L1. Then, the relative modal delay $\Delta\tau$ of fiber **60** was calculated using equation (2B), which assumes $\Delta 0$=1%, where $\alpha_{60} < \alpha_{40}$. After the relative modal delay $\Delta\tau$ and the time delay Δt per kilometer of primary fiber **40** was calculated, equation (3A) was used to calculate the length L2 of fiber **60** needed to produce a modal delay of the same magnitude but opposite sign as the chromatic modal dispersion associated with primary fiber **40**.

[0104] In Table 1, "EX" stands for "example," D stands for the amount of chromatic dispersion at the peak wavelength λ_P=850 nm and is measured in units of ps/nm·km, the parameter λ_{01} is the main wavelength of VCSEL light source **24** measured in nanometers for the fundamental transverse mode LP_{01} and generally represents the peak wavelength λ_{P40} for primary fiber **40**, $\Delta\lambda_{max-c}$ is the center-wavelength difference measured in nanometers, and Δt is the maximum time delay needed in units of nanoseconds to compensate fiber **60** for the chromatic modal dispersion along the fiber.

TABLE 1

Examples for Δ = 1%

EX	D	λ_{01}	$\Delta\lambda_{max-c}$	L1 (m)	$\Delta\alpha$	Δt (ns)	L2 (m)
1	−100	850	1	100	−0.2	0.01	5
2	−100	850	0.8	300	−0.2	0.024	12
3	−100	850	0.7	300	−0.4	0.021	5.25
4	−100	850	1	600	−0.3	0.06	20
5	−100	850	0.8	300	−0.2	0.024	11.8
6	−56	980	1	300	−0.3	0.0168	6.3
7	−34	1060	1	300	−0.3	0.0102	4.1

[0105] The data of Table 1 indicate that the length L2 of compensating fiber **60** is substantially insensitive to a slight variation in the VCSEL central (main) wavelength λ_{01}, leaving the choice of the length L2 to be primarily determined by the length L1 of primary fiber **40** and the VCSEL radial wavelength dependence as described by $\Delta\lambda_{max-c}$. We note here that in order to generate the necessary modal delay in just a single multimode fiber while also compensating for spatial chromatic dispersion, the $\Delta\alpha$ is −0.01, which is far less than the AU for compensating fiber **60**.

[0106] In the calculation in Table 1, the chromatic modal dispersion of compensating fiber **60** was ignored because it was considered far smaller than that of primary fiber **40** and, accordingly, its relative effect was deemed negligible. To obtain more accurate results, one can use the following equation:

$$L2 = \frac{(L1 + L2) \cdot D \cdot \Delta\lambda_{max-c}}{|\Delta\tau_{max}|} \tag{4A}$$

wherein solving for L2 yields the relationship:

$$i.\ \ L2 = \frac{L1 \cdot D \cdot \Delta\lambda_{max-c}}{|\Delta\tau_{max}| - D \cdot \Delta\lambda_{max-c}}. \tag{4B}$$

[0107] Table 2 below illustrates several additional examples similar to those shown in Table 1, but wherein primary fiber **40** and compensating fiber **60** each have a relative refractive index Δ=0.5% and a core diameter of 50 μm. In Examples 8 and 9, primary fiber **40** is optimized for operation with a light source **24** generating light at a peak wavelength $\lambda_{P40}=\lambda_{01}$=850 nm. In Example 10, primary fiber **40** is optimized for operation with a light source **24** generating light at a peak wavelength $\lambda_{P40}=\lambda_{01}$=980 nm. In Example 11, primary fiber **40** is optimized for operation with a light source **24** generating light at a peak wavelength $\lambda_{P40}=\lambda_{01}$=1,060 nm. As in the calculation for Table 1, in Table 2, the chromatic modal dispersion of compensating fiber **60** was deemed negligible and was therefore ignored.

TABLE 2

Examples for $\Delta = 1\%$

EX	D	λ_{01}	$\Delta\lambda_{max-c}$	L1 (m)	$\Delta\alpha$	Δt (ns)	L2 (m)
8	−100	850	1	100	−0.2	0.01	10
9	−100	850	1	600	−0.3	0.06	40
10	−56	980	1	300	−0.3	0.0168	12.7
11	−34	1060	1	300	−0.3	0.0102	8.2

[0108] In addition to compensating for the chromatic dispersion effects caused by differences in the particular spectra of light sources **24**, compensating fiber **60** may be used to compensate for modal dispersion in primary fiber **40** that arises in the case where λ_{01} is substantially different from λ_{P40}. For example, if primary fiber **40** has a peak wavelength $\lambda_{P40=850}$ nm, then compensating fiber **60** can compensate for chromatic dispersion arising from using a light source **24** having a center operating wavelength λ_{CW} of 980 nm or 1,060 nm, or 1,310 nm, which will give rise to an additional modal delay from compensating fiber **60**.

[0109] In the case where compensating fiber **60** is used to compensate for the modal dispersion from primary fiber **40** used at an operating wavelength that is substantially different from λ_{P40}, the length L2 for fiber **60** may not be negligible compared to the length L1 for fiber **40**. This means that the chromatic and modal dispersion in compensating fiber **60** may no longer be negligible and would need to be taken into account.

[0110] Thus, in calculating the length L2 of compensating fiber **60** necessary to compensate both for the modal dispersion of primary fiber **40** and for the chromatic dispersion arising in the compensating fiber **60**, the following equation applies, wherein the amount of modal dispersion is MD:

$$b.\ L2 = \frac{MD + (L1 + L2) \cdot D \cdot \Delta\lambda_{max-c}}{|\Delta\tau_{max}|} \tag{4C}$$

wherein solving for L2 yields the relationship:

$$1.\ L2 = \frac{L1 \cdot D \cdot \Delta\lambda_{max-c} + MD}{|\Delta\tau_{max}| - D \cdot \Delta\lambda_{max-c}}. \tag{4D}$$

[0111] Table 3 below illustrates examples where compensating fiber **60** is used to compensate for the chromatic and modal dispersion of primary fiber **40** in the situation where λ_{01} is substantially different from the peak wavelength λ_{P40}. Table 3 includes the maximum mode delay MD (ns) at the peak wavelength λ_{P40}.

TABLE 3

Examples for $\Delta = 1\%$ and for wavelengths other than λ_{P40}

EX	D	λ_{CW}	$\Delta\lambda_{max-c}$	L1 (m)	$\Delta\alpha$	MD(ns)	Δt (ns)	L2 (m)
12	−56	980	1	300	−0.6	0.3	0.0168	16.0
13	−34	1,060	1	300	−0.6	0.5	0.0102	25.7

[0112] The system **10** described herein is well suited to transmitting data at high rates, such as rates faster than or equal to 25 GB per second or greater than 40 GB per second. In an example embodiment, system **10** can have multiple fibers **60** that operate in parallel, one or more fibers **40** being concatenated with each fiber **60**. The fiber **60** may also comprise a portion of a ribbon cable or other group of cables including 4, 12, 24, etc. fibers **60** for parallel optics configurations.

[0113] In another set of examples EX 14 through EX 16 set forth in Table 4 below, compensating fiber **60** has a different maximum relative refractive index Δ_0 from the primary fiber **40**, which is usually 1%. Because of the use of compensating fiber **60**, wherein $\alpha_{60}<\alpha_{40}$, fewer modes can propagate in the compensating fiber for a given maximum relative refractive index. To increase the number of modes supported by compensating fiber **60**, one can increase the maximum relative refractive index Δ_0.

[0114] All the fibers of examples EX 14 through EX 16 in Table 4 have Δ_0=1.5%. The compensating fiber **60** having a higher maximum relative refractive index Δ_0 than it might otherwise have if used as a conventional multimode fiber enables the use of shorter lengths L2. In an example, compensating fiber **60** has a maximum relative refractive index Δ_0 of about 1.5%, while in another example the compensating fiber has a maximum relative refractive index Δ_0 that is in the range from about 0.5% to about 1% larger than that of primary fiber **40**.

TABLE 4

Examples for compensating fibers with $\Delta_0 = 1.5\%$

EX	D	λ_{01}	$\Delta\lambda_{max-c}$	L1 (m)	$\Delta\alpha$	Δt (ns)	L2 (m)
14	−100	850	1	500	−0.2	0.05	16.7
15	−100	850	0.5	500	−0.2	0.025	8.3
16	−100	850	0.3	300	−0.3	0.009	2

[0115] In an example, compensating fiber **60** has length L2 that in respective examples has L2≤20 m, L2≤10 m and L2≤5 m. In an example, primary fiber **40** has a length L1≥100 m, or L1≥300 m, or even L1≥500 m. In an example embodiment, the combination of primary fiber **40** and one or more compensating fibers **60** concatenated thereto defines a link bandwidth BW_L, wherein in one example BW_L>3,000 MHz·km, and in another example BW_L>5,000 MHz·km and in another example BW_L>7,000 MHz·km and in another example BW_L>10,000 MHz·km.

[0116] In an example embodiment, compensating fiber **60** can be a bend insensitive fiber, as described above in connection with FIG. **3C**. As discussed above, an example bend-insensitive compensating fiber **60** has trench **67** adjacent core **66**. However, in this example embodiment, trench **67** also allows the highest modes of the higher-order modes to propagate over substantial distances, whereas before these highest modes were lossy and so did not substantially contribute to the mode delay.

[0117] Thus, in an example embodiment of bend-insensitive compensating fiber **60**, the parameters defining trench **67** are selected to minimize the adverse effects of the propagation of the highest modes while also providing the desired bend insensitivity.

[0118] Table 5 below sets forth example design parameters for an Example 17 of compensating fiber **60** wherein the compensating fiber is bend insensitive. FIG. **9** is a plot of the relative refractive index profile Δ(%) versus the radius of an example bend-insensitive compensating fiber **60** and shows the various design parameters (namely, relative refractive index values Δ_{1MAX}, Δ_2, Δ_3, Δ_4 and radii r_1 through r_4), examples of which are set forth in Table 5 below. The radii r_1 through r_4 are in microns and the relative refractive index values are in "Δ %." The trench **67** is shown by way of example as being spaced apart from core **66** by a distance (r_2-r_1) and thus can be considered as residing in cladding **68**. Strictly speaking, in this geometry, cladding **68** comprises an inner and outer cladding corresponding to the relative refractive indices Δ_2 and Δ_4. Also, $\Delta_{1MAX}=\Delta_0$.

TABLE 5

Design parameters for
Example 17 of compensating fiber 60

Parameter	Example Value
Δ_{1MAX}	1
r_1	25
α_{60}	1.796
r_2	26.72
Δ_2	0
r_3	32.22
Δ_{3MIN}	−0.5
r_4	62.5
Δ_4	0

[0119] FIG. **10** is a plot of the mode group number vs. the relative delay (ns/km) for compensating fiber **60** of Example 17 of Table 5 for an operating wavelength of 850 nm. FIG. **10** shows all mode groups for compensating fiber **60**. Because the highest modes of the higher-order modes can propagate over the entire length of system **10**, the maximum relative delay is slightly higher for a bend-insensitive compensating fiber **60** than for the more conventional form of the compensating fiber such as that shown in FIG. **3**B.

[0120] However, the spread of the highest modes (i.e., the higher-order modes having the highest mode group numbers) is not substantial, and the relationship between the relative delay and the mode group number is smooth. This characteristic is also maintained at an operating wavelength of 1,060 nm so that the same bend-insensitive compensating fiber **60** can be used for a range of operating wavelengths, including at least those in the range from 850 nm to 1,060 nm.

[0121] FIG. **11** is a plot of differential modal delay (DMD), which is a measure of the average relative modal delay as measured in ns/km, vs. radial launch offset (μm) for an example compensating fiber **60** with $\alpha_{60}\approx 1.88$, with the fiber scaled to 1,000 m in length. The amount of DMD as shown in FIG. **10** corresponds to the prediction of the differential (relative) modal delay $\Delta\tau$ shown in FIG. **8**.

[0122] FIG. **12** is a plot of the relative delay Δt (ps) vs. radial launch offset (μm) for an example primary fiber **40** that meets the OM4 standard as defined in TIA-492-AAAD. This OM4 quality primary fiber **40** of length L1=1 km was then concatenated with a 70 m compensating fiber **60**, whose DMD properties are shown in FIG. **11**.

[0123] FIG. **13** is a plot similar to FIG. **12** for concatenated primary and secondary fibers **40** and **60**. The DMD curve of the combined primary and compensating fibers **40** and **60** is negative or tilted toward negative values when moving from the center (zero offset) to higher offset values (toward the edge of the core), which indicated that the modal delay of the link is altered by the introduction of the 70 m. The amount of tilting can be manipulated by setting the length of compensating fiber **60** to match the spatial chromatic dispersion from a specific VCSEL and primary fiber **40**.

[0124] FIG. **13** shows two curves. One of the curves is a heavy solid line and represents the total delay provided by concatenated primary and secondary fibers **40** and **60** and is labeled as "Delay (70+1 km)." The other curve is a dashed line and represents the addition of the delay measured based on the delay of a 70 m compensating fiber **60** and the delay of a 1 km primary fiber **40** in two separate measurements and is labeled as ("Delay (70 m)+Delay (1 km)." The two curves follow each other closely with a relatively large region of substantial overlap. This characteristic means that the delays are substantially linearly accumulative and therefore approximately additive. This allows for concatenating two or more compensating fibers **60** (i.e., optically connecting two or more sections of the compensating fibers) to provide for the amount of delay needed for system **10**.

[0125] Two additional examples illustrate the use of compensating fibers **60** for use in several configurations for system **10**, where fibers **40** and **60** each have a relative refractive index Δ of approximately 1% and a core diameter of approximately 50 μm. The example primary fibers are optimized for operation with an example light source **24** generating light at a wavelength in the 1200-1400 nm wavelength range. In these examples, source **24** comprises four lasers transmitting data at a bit rate of 25 Gb/s at wavelengths of 1290, 1310, 1330 and 1350 nm.

[0126] In the two additional examples, the distribution of one thousand uncompensated primary fibers was modeled, where the primary fiber comprises a graded index core having a peak refractive index ranging from 0.85 to 1.15%, a core radius ranging from 24.3 to 25.4 microns, a core alpha ranging from 1.97 to 2.04. The primary fiber further comprises a trench spaced from the core by 1.1 to 1.7 microns, having a width of approximately 6 microns and having a relative refractive index ranging from −0.27 to −0.33%. The system reach is calculated by dividing the calculated overfilled bandwidth in Ghz·km by 25 Gb/s, resulting in values between 50 m and 450 m.

[0127] It is desirable to increase the probability of producing multimode fibers capable of system reaches of at least 300 m for data rates of 25 Gb/s or greater, and this can be achieved by adding a short length of compensating fiber. For example, the compensating fiber could comprise a fiber optic jumper cable having a length of 0.5 m, 1 m, 2 m, 5 m, or any lengths therebetween.

[0128] The use of a small length of the appropriate compensation fiber **60** expands the range of alpha values that yield a system reach of at least 300 m. In an example, combining compensation fiber **60** having an alpha value of 2.5 with a primary fiber **40** having an alpha value in the range of 2.00 to 2.01 enables system **10** to have a reach of 300 m for all wavelengths in the 1290-1350 nm range and a source transmitting data at a rate of 25 Gb/s. Combining a compensation fiber **60** having an alpha value of 1.62 with a primary fiber **40** having an alpha value in the range of 2.01 to 2.02 enables system **10** to have a reach of 300 m for all wavelengths in the 1290-1350 nm range and a source transmitting data at a rate of 25 Gb/s.

[0129] One example multimode optical fiber system **10** comprises a primary multimode optical fiber having a length L1 and having a first relative refractive index profile with a first alpha α_{40} in the range of 1.97 to 2.04, configured to provide for a minimum amount of intermodal dispersion of guided modes at wavelengths in the 1200-1400 nm range; and a compensating multimode optical fiber having a length L2<L1 and that is optically coupled to the primary multimode optical fiber, wherein the compensating multimode optical fiber has a second relative refractive index profile with a second alpha value $\alpha 60$ in the range $2.3 \leq \alpha_{60} \leq 2.7$, i.e. $0.3 \leq (\alpha_{60} - \alpha_{40}) \leq 0.8$. In an example, the total link length LT=L1+L2 is greater than about 100 m, more preferable greater than about 200 m and even more preferably greater than about 300 m. In some embodiments, L1/L2, the ratio of the lengths of primary fiber L1 and compensation fiber L2, is greater than 20, for example L1/L2>40, L1/L2>60, L1/L2>80, L1/L2>90, L1/L2>100. In some embodiments, 20<L1/L2<200, for example 40<L1/L2<200, 40<L1/L2<100 or 80<L1/L2<100.

[0130] Another example of multimode optical fiber system **10** comprises a primary multimode optical fiber **40** having a length L1 and having a first relative refractive index profile with a first alpha α_{40} in the range of 1.97 to 2.04, configured to provide for a minimum amount of intermodal dispersion of guided modes at wavelengths in the 1200-1400 nm range; and a compensating multimode optical fiber **60** having a length L2<L1 and that is optically coupled to the primary multimode optical fiber, wherein the compensating multimode optical fiber has a second relative refractive index profile with a second alpha value α_{60} in the range $1.4 \leq \alpha_{60} \leq 1.8$, i.e. $-0.3 \geq (\alpha_{60} - \alpha_{40}) \geq -0.8$.

[0131] The total length LT=L1+L2 is preferably greater than about 100 m, more preferably greater than about 200 m and even more preferably greater than about 300 m. In some embodiments, L1/L2, the ratio of the lengths of primary fiber L1 and compensation fiber L2, is greater than 20, for example L1/L2>40, L1/L2>60, L1/L2>80, L1/L2>90, L1/L2>100. In some embodiments, 20<L1/L2<200, for example 40<L1/L2<200, 40<L1/L2<100 or 80<L1/L2<100.

[0132] In another example embodiment, compensating fiber **60** has an alpha value of around 1.55, a core diameter of 50 microns and core delta of 1%. FIG. **14**A is a plot similar to that of FIG. **12** and shows that the example compensating fiber **60** provides a significant left-tilt DMD delay in unit length at 850 nm and at higher wavelengths.

[0133] An aspect of the disclosure is a method of converting an OM4 fiber, which is the primary fiber optimized for around 850 nm, to a multimode optical fiber link **70** that is optimized for around 1060 nm. The centroid delay of 40 m of such a fiber measured at 1042 nm (which is close to 1060 nm) is shown in FIG. **14**A. At the 20 micron offset or radial position, the delay is around −160 ps. Therefore, for each meter, this fiber provides a delay of 4 ps at the radial offset of 20 microns.

[0134] The DMD centroid of 547 m of OM4 fiber at 1042 nm was also measured and is plotted in FIG. **14**B. At 1042 nm, the delay is right tilt for the OM4 fiber, although it should be centered around a zero delay around 850 nm. On the other hand, the centroid delay of the fiber having a low alpha value is left-tilted, as shown in FIG. **14**A. By properly choosing the length ratio L1/L2 between primary and compensating fibers **40** and **60** that have different tilts such as shown in FIGS. **14**A and **14**B, the multimode link **70** can have a substantially flat centroid delay, or delay vs. offset centered about zero.

[0135] An example optical fiber link **70** was formed having a ratio of 7.5:1 between the OM4 primary fiber **40** and the compensating fiber **60**. Optical fiber links **70** with LT=200 m and LT=300 m link were formed. For link **70** where LT=200 m link, L=177 m and L2=23 m. For link **70** where LT=300 m, L1=265 m and L2=35 m. In an example, the two links of LT=200 m and LT=300 m link were concatenated to form a 500 m combined link which is long enough for a DMD measurement at 1042 nm.

[0136] FIG. **15** is a plot of the signal strength (relative units) versus time of an example optical fiber link **17** formed using OM4 fibers having the properties of FIGS. **14**A and **14**B. The plot of FIG. **15** indicates that the DMD of optical fiber link **70** is generally flat but has slight left tilt at 1042 nm. The link bandwidth BW_L of this combined link **70** was measured to have a bandwidth of 20 GHz through a direct bandwidth measurement based on frequency sweeping method at 1060 nm. The modal link expressed in bandwidth-length product is 10 GHz·km for this combined link **70**, which indicates the link has very high performance.

[0137] The foregoing description provides exemplary embodiments to facilitate an understanding of the nature and character of the claims. It will be apparent to those skilled in the art that the various modifications to these embodiments can be made without departing from the spirit and scope of the appended claims.

What is claimed is:

1. An optical fiber link, comprising:

a primary multimode optical fiber having a length L1 and having a first relative refractive index profile with a first core region having a first alpha value α_{40} of about 2.1 and generally configured to provide for a minimum amount of intermodal dispersion of guided modes at a peak wavelength λ_{P40} in the range from 840 nm to 860 nm, the primary multimode optical fiber having a first bandwidth BW_{40} of 4 GHz·km or greater; and

a compensating multimode optical fiber having a length L2<L1 and that is optically coupled to the primary multimode optical fiber, wherein the compensating multimode optical fiber has a second relative refractive index profile having a second core region with a second alpha value α_{60}, and wherein $-0.9 \leq (\alpha_{60} - \alpha_{40}) \leq -0.1$.

2. The optical fiber link according to claim **1**, wherein, the compensating multimode optical fiber has a peak wavelength λ_{P60} greater than 880 nm.

3. The optical fiber link according to claim **1**, wherein at least one of the primary multimode optical fiber and the compensating multimode optical fiber comprises a fluorine doped depressed region in the cladding region of the optical fiber.

4. The optical fiber link according to claim **1**, wherein the compensating multimode optical fiber has:

a) a bandwidth BW_{60} of less than 500 MHz·km;

c) a peak wavelength $\lambda_{P60} > 880$ nm; and

b) a maximum relative refractive index Δ_0 and wherein $1\% \leq \Delta_0 \leq 1.5\%$.

5. The optical fiber link according to claim **1**, wherein the compensating multimode optical fiber has an alpha value $\alpha 60$ greater than about 1.2 and less than about 2.0.

6. The optical fiber link according to claim **1**, wherein the compensating multimode optical fiber has core radius r_1 of about 25 microns and a maximum core delta Δ_{1MAX} of about 1%.

7. The optical fiber link according to claim **1**, wherein the optical fiber link has a link bandwidth BW_L of 4 GHz·km or greater at a second wavelength in the range from 880 nm to 1600 nm.

8. The optical fiber link according to claim **5**, wherein the second wavelength is in the range from 880 nm to 1360 nm.

9. The optical fiber link according to claim **8**, wherein the second wavelength is in the range from 880 nm to 1100 nm.

10. The optical fiber link according to claim **9**, wherein the second wavelength in the range from 880 nm to 1000 nm.

11. The optical fiber link according to claim **1**, wherein the optical fiber link has a link bandwidth BW_L of 5 GHz·km or greater at a second wavelength in the range from 880 nm to 1600 nm.

12. The optical fiber link according to claim **11**, wherein the second wavelength is in the range from 880 nm to 1360 nm.

13. The optical fiber link according to claim **12**, wherein the second wavelength is in the range from 880 nm to 1100 nm.

14. The optical fiber link according to claim **12**, wherein the second wavelength is in the range from 880 nm to 1000 nm.

15. The optical fiber link according to claim **1**, wherein the optical fiber link has a link bandwidth BW_L of 7 GHz·km or greater at a second wavelength in the range from 880 nm to 1600 nm.

16. The optical fiber link according to claim **15**, wherein the second wavelength is the range from 880 nm to 1360 nm.

17. The optical fiber link according to claim **16**, wherein the second wavelength range is in the range from 880 nm to 1100 nm.

18. The optical fiber link according to claim **17**, wherein the second wavelength range is in the range from 880 nm to 1000 nm.

19. An optical fiber link, comprising:

a primary multimode optical fiber having a length L1 and having a first relative refractive index profile with a first core region having a first alpha value α_{40} of about 2.1 and generally configured to provide for a minimum amount of intermodal dispersion of guided modes at a peak wavelength λ_{P40} in the range from 840 nm to 860 nm, the primary multimode optical fiber having a first bandwidth BW_{40} of 4 GHz·km or greater;

a compensating multimode optical fiber having a length L2<L1 and that is optically coupled to the primary multimode optical fiber, wherein the compensating multimode optical fiber has a second relative refractive index profile with a second core region having a second alpha value α_{60}, and wherein $-0.9 \leq (\alpha_{60}-\alpha_{40}) \leq -0.1$; and

wherein the optical fiber link has a link bandwidth BW_L of 4 GHz·km or greater at a second wavelength in a range from 880 nm to 1600 nm.

20. The optical fiber link according to claim **19**, wherein the optical fiber link has a length LT=L1+L2, and wherein the optical fiber link supports transmission of respective optical signals in the first and second wavelength ranges at data rates of at least 16 Gb/s over the length LT of the optical fiber link.

21. The optical fiber link according to claim **19**, wherein the optical fiber link length LT is in the range from 50 m to 800 m.

22. An optical fiber system, comprising:

the optical fiber link of claim **19**; and

a transmitter comprising a VSCEL light source optically coupled to an end of optical fiber link.

23. The optical fiber system according to claim **22**, wherein the optical fiber system supports transmission of optical signals at a data rate of 10 Gb/s or greater.

24. The optical fiber system according to claim **22**, wherein the data rate is 16 Gb/s or greater.

25. The optical fiber system according to claim **22**, wherein the data rate is 25 Gb/s or greater.

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