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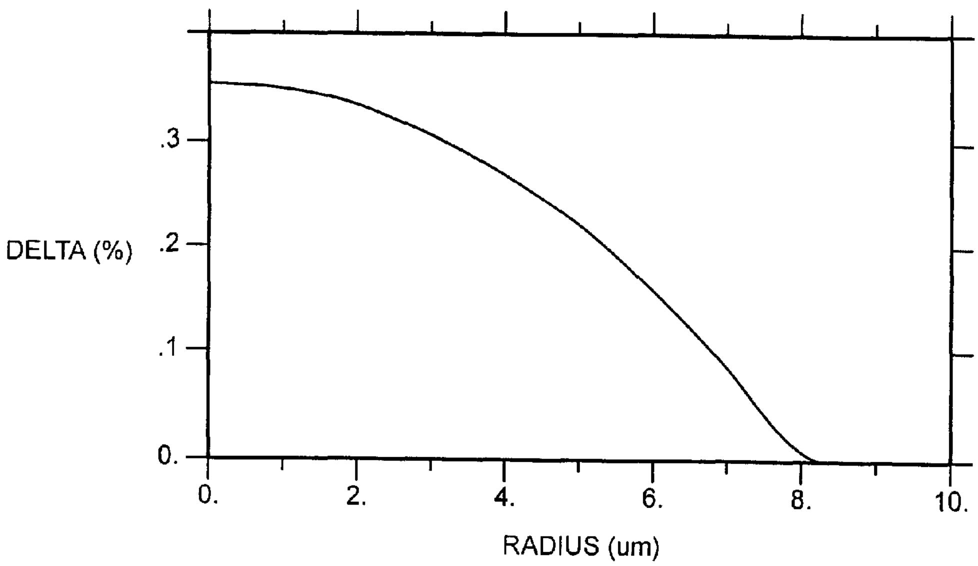

(57) Abstract: An optical fiber is disclosed herein comprising a core having an alpha parameter in the range of approximately 2 to approximately 8, a maximum index percent difference between the core and a cladding in the range of approximately 0.3% to approximately 0.5% and a core diameter in the range of approximately 6.0 to approximately 16.0 μm and a cladding. The optical fiber has a bandwidth of at least approximately 0.6 GHz.km at 850 nm, and is configured for multimode operation at a wavelength less than 1300 nm and single mode operation at a wavelength of at least approximately 1300 nm. The fiber also has significantly reduced intermodal noise. Also disclosed herein is a method of designing such a fiber, a fiber optic system provided such a fiber and a method of operating a fiber optic system with such a fiber.

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BROADBAND ACCESS OPTIMIZED FIBER AND METHOD OF MAKING

FIELD OF THE INVENTION

[0001] The present invention is directed generally to optical fiber for telecommunications and more specifically to an optical fiber capable of multimode operation at wavelengths below about 1300 nm and single mode operation at wavelengths above about 1300 nm, the optical fiber having reduced intermodal noise.

BACKGROUND OF THE INVENTION

[0002] The optical fiber typically used to wire homes and small businesses has undesirably low bandwidth. Currently, 850 nm multimode fiber is used for wiring homes and small businesses because the various system components (e.g. lasers, receivers) used in conjunction with this fiber are inexpensive. However, conventional 850 nm multimode fiber can support a relatively low bit rate.

[0003] Typically, upgrading to a higher bandwidth system requires replacing the existing fiber. Conventional 850 nm multimode fiber is incompatible with higher bit rate components, such as 1300 nm single mode lasers and receivers. Therefore, it is not possible to upgrade a conventional 850 nm multimode system to a higher bit rate system without replacing all of the components, especially the fiber. Typically, to upgrade a conventional 850 nm multimode system to a higher bit rate system, the conventional 850 nm multimode fiber is replaced with a 1300 nm single mode fiber such as SMF28™ single-mode optical fiber manufactured by Corning Incorporated.

[0004] Replacing the existing fiber can be expensive. For example, replacing the 850 nm multimode fiber often entails digging up the old fiber and laying the new fiber in its place. Additionally, fiber replacement often requires significant reconstruction of the home or office installation. Thus, fiber replacement is often a costly and time-consuming process.

[0005] Rather than replacing old fiber and laying new fiber, it would be preferable to initially install a fiber capable of multimode operation at 850 nm and single mode operation at 1300 nm. Thus, upgrading a system with such a fiber would only require replacing system components. Experimental fibers capable of both multimode operation at 850 nm and single mode operation at 1300 nm have been reported in the literature, however, those fibers were step indexed and tended to have very low bandwidth at 850 nm. Therefore, it would be advantageous to have a fiber capable of multimode operation at 850 nm with a large bandwidth and single mode operation at 1300 nm.

[0006] An additional problem associated with multimode fibers is intermodal noise. Intermodal noise is related to a variation of the optical intensity at a given optical fiber output location due to optical interference between modes of different phase. Many factors may act singly or in combination to produce phase changes that can cause intermodal noise. Example factors include, changes in temperature, mechanical distortions (including movement or vibration), as well as changes in optical source wavelength.

[0007] Intermodal noise is a common problem in multimode fibers used with highly coherent light sources, e.g., lasers. This is because the relative coherence of the modes allows the modes to effect the intensity of the light by interfering with each other. Less coherent sources, such as LED's, have a short coherence length and therefore are only subject to intermodal noise in very short lengths of fiber. However, LED sources are polychromatic which causes significant pulse broadening in the fiber. This is a problem because pulse broadening reduces bandwidth. Therefore, it would be advantageous to have a fiber designed for operation with coherent light sources which does not suffer from intermodal noise.

SUMMARY OF THE INVENTION

[0008] Disclosed herein is an optical fiber, comprising a core having a refractive index profile that comprises an alpha profile with an alpha parameter in a range from approximately 2 to approximately 8, a maximum refractive index percent difference between the core and a cladding in a range from approximately 0.26% to approximately 0.5% and a core diameter in a range from approximately 6.0 to approximately 16.0 μm and a cladding, wherein the optical fiber has a bandwidth of at least approximately 0.6 GHz.km at 850 nm, and is configured for multimode operation at a wavelength less than 1300 nm. Cut off wavelength of the optical fiber is in the range from about 1050 nm to 1300 nm so that single mode operation is exhibited at a wavelength of at least approximately 1300 nm.

In preferred embodiments the core diameter has a range of approximately 6.0 to 14.0 μm or a maximum refractive index percent difference in the range of approximately 0.3% to 0.4%. A preferred range of alpha parameter is from approximately 2 to approximately 4.

Preferably the effective area of the optical fiber disclosed herein is greater than 70 μm^2 at 1550 nm, and more preferably greater than 90 μm^2. The pin array bend loss is preferably less than 4 dB at 1550 nm and more preferably less than 2 dB. In a preferred embodiment the mode field diameter is greater than or equal to 10 μm at 1550 nm.

[0009] In a preferred embodiment, the optical fiber comprises a core and a cladding, wherein the optical fiber is a multimode fiber at an operating wavelength and is configured in accord with a given operating wavelength, the desired bandwidth, and the length of the fiber. Preferably, the peak modal bandwidth wavelength of the fiber is offset from the operating wavelength by an amount sufficient to reduce modal noise. The preferred amount of the offset depends upon fiber length, desired bandwidth, and operating wavelength.

In yet another preferred embodiment, the alpha parameter is approximately 2, the maximum refractive index percent difference between core and clad has a range from approximately 0.35% to 0.40%, and the core diameter is in the range from approximately 14.0 to 16.0 μm. The embodiment provides an optical fiber having, at 1550 nm, an effective area greater than 90 μm^2 and a mode field diameter greater than 11 μm at 1550 nm. Pin array bend loss is less than 2 dB at 1550 nm.

In an additional preferred embodiment, the alpha parameter is approximately 3, the maximum refractive index percent difference between the core and the cladding is in the range of approximately 0.35% to approximately 0.4% and the core diameter is in the range of approximately 12.0 to approximately 15.0 μm, to provide a waveguide fiber having effective area greater than 85 μm^2 at 1550 nm, and mode field diameter greater than 10.5 μm at 1550 nm. The pin array bend loss is less than 4 dB at 1550 nm.

In an additional preferred embodiment, the alpha parameter is approximately 4, the maximum refractive index percent difference between the core and the cladding is in the range from approximately 0.3% to approximately 0.4% and the core diameter is in the range from approximately 12.0 to approximately 16.0 μm, to provide a waveguide fiber having, at 1550 nm, an effective area greater than 85 μm^2, and mode field diameter greater than 10.5 μm. The pin array bend loss at 1550 nm is less than 3.5 dB.

In an additional preferred embodiment, the offset between peak bandwidth wavelength and operating wavelength is selected to provide respective group time delays for modes which are either all positive or all negative. The sign of the delay is determined with reference to the arrival time of the lowest order mode (LP_{01} mode). A positive group time delay pertains to a mode which arrives before the LP_{01} mode and a negative arrival time is the converse.

In another preferred embodiment the absolute value of the sum of the respective group time delays is greater than 0.

[0010] In another preferred embodiment, disclosed herein is a method of designing an optical fiber having a bandwidth of at least 0.6 GHz.km at 850 nm in multimode operation and being in single mode operation at a wavelength of at least approximately 1300 nm, comprising, determining for a given length of optical fiber a minimum difference between the operating wavelength and a peak modal bandwidth wavelength such that the difference in the optical path lengths of the modes in multimode operation is greater than at least one coherence length of the fiber, the coherence length being associated with a source utilized to launch light within the optical fiber at the operating wavelength, and determining a refractive index profile associated with the optical fiber in accordance with the minimum difference.

In an embodiment of the method of the second aspect of the invention, determining the minimum difference in offset between peak bandwidth wavelength and operating wavelength includes the step of calculating a speckle constant gamma, γ. The speckle constant is calculated as a function of bandwidth, line width of the light source, intensity of the light source, and length of the optical fiber.

In another preferred embodiment, the step of determining a minimum difference includes having the respective group delay times of the modes be all negative or all positive.

In another preferred embodiment, the step of determining an index profile includes at least one of determining the operating wavelength, the desired bandwidth, or the length of the optical fiber during operation.

[0011] Also disclosed herein is an optical fiber system comprising an optical fiber with a core having a refractive index profile having an alpha profile with an alpha parameter from approximately 2 to approximately 8, a maximum refractive index percent difference between the core and a cladding from approximately 0.3% to approximately 0.5% and a core diameter of approximately 6.0 to approximately 16.0 μm and a light source optically coupled to the optical fiber. The alpha parameter, the maximum percent refractive index difference, and the core diameter are chosen to provide an offset between peak bandwidth wavelength and operating wavelength sufficient to reduce intermodal noise at the operating wavelength.

[0012] Also disclosed herein is a method of operating an optical fiber system comprising providing an optical fiber wherein the optical fiber is a multimode fiber at an operating wavelength and has a peak modal bandwidth wavelength offset from the operating wavelength and operating a light source at the operating wavelength.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The foregoing and other features, aspects and advantages of the present invention will become apparent from the following description, appended claims and the exemplary embodiments shown in the drawings, which are briefly described below. It should be noted that unless otherwise specified like elements have the same reference numbers.

[0014] Figure 1 is a schematic diagram of an experimental apparatus.

[0015] Figure 2A is a detail view of the fiber joint in Figure 1 illustrating aligned fibers.

[0016] Figure 2B is a detail view of the fiber joint in Figure 1 illustrating offset fibers.

[0017] Figure 3 is a plot comparing simulation data with actual data.

[0018] Figure 4 is a plot illustrating the coherence damping for various source linewidths.

[0019] Figure 5 is a simulated spectra for a fiber length of 10 meters.

[0020] Figure 6 is a simulated spectra for a fiber length of 20 meters.

[0021] Figure 7 is a simulated spectra for a fiber length of 50 meters.

[0022] Figure 8 is a simulated spectra for a fiber length of 100 meters.

[0023] Figure 9 is a simulated spectra for a fiber length of 500 meters.

[0024] Figure 10 is a simulated spectra for a fiber length of 1000 meters.

[0025] Figure 11 is a simulated spectra for a fiber length of 2000 meters.

[0026] Figure 12 is a simulated spectra for a fiber length of 5000 meters.

[0027] Figure 13 is a chart of optimum values of the profile parameter versus wavelength.

[0028] Figure 14 is a refractive index profile of an optical fiber, as disclosed herein.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0029] The inventors have discovered that it is possible to design a fiber capable of multimode operation at 850 nm having high modal bandwidth and single mode operation at wavelengths of at least approximately 1300 nm. This can be accomplished by producing a fiber with an alpha profile having an alpha parameter of approximately 2-8, a maximum index percent difference between the core and a cladding of approximately 0.26%-0.5% and a core diameter of approximately 6.0-16.0 μm. In addition to being capable of both multimode and single mode operation, these fibers have higher effective areas and lower pin array bend loss than conventional single mode optical waveguide fiber such as SMF-28™, available from Corning, Inc.

[0030] The alpha profile is a graded-index profile which is described by the following power law equation,

$$n(r) = n_0\sqrt{1-2\Delta\left(r/a\right)^{\alpha}}$$

where, n_0 is the maximum refractive index of the core of the optical fiber; is the index difference between the indices of refraction of the core and cladding, n_c of the optical fiber; a = radius of the core; r = radial position (0 < r < a) measured from the center of the core toward the cladding; and (alpha) is a parameter. The maximum relative index difference Δ may be exactly defined as, $\Delta = \left[\frac{n_0^2 - n_c^2}{2{n_0}^2}\right]$. It will be understood that the term refractive index difference (or, simply, index difference) Δ and relative refractive index difference (or, simply, relative index difference) Δ are used interchangeably herein. The Δ is also referenced in the art as relative refractive index. The maximum index difference Δ may be approximated as $\Delta \approx \frac{n_0 - n_c}{n_o}$. Generally, the maximum index difference is multiplied by 100 and reported in percent. The approximation is accurate to within 1% of the exact value Δ. For practical purposes the two equations may be used interchangeably.

[0031] To produce a fiber having high modal bandwidth at 850 nm in multimode operation and capable of single mode operation at 1300 nm, the fiber preferably has an alpha parameter in the range of approximately 2 to approximately 8, more preferably approximately 2 to approximately 4. More preferably, the alpha parameter is in the range of approximately 2 to approximately 3.3. More preferably, the alpha parameter is in the range of approximately 2.5 to approximately 3.3. An alpha parameter that is too large or small can result in an unacceptable decrease in modal equalization (modal equalization occurs when all of the modes travel with the same velocity). Because bandwidth is a maximum at modal equalization, an increase in the difference in the modal velocities results in a decrease in bandwidth.

[0032] The maximum index difference Δ between the core and the cladding is preferably in the range of approximately 0.26% to approximately 0.5%. More preferably, the maximum index difference Δ is in the range of 0.3%-0.5%, and more preferably still in the range of 0.3% to 0.4%. A maximum index difference Δ that is too low results in an unacceptably high bend loss. A maximum index difference Δ that is too high can require an unacceptably small core diameter.

[0033] It is preferable that the diameter of the fiber core is in the range of approximately 6.0 to approximately 16.0 μm. More preferably, the core diameter is in the range of approximately 8.0 to approximately 14.0 μm. Even more preferably, the core diameter is approximately 12.0 μm. If the diameter of the core is too small, then it may become difficult to connect fiber segments because even small absolute misalignments of the fiber segments at the joint results in a large percentage misalignment of the fiber cores. If the core diameter is too large, then too many modes may propagate through the fiber, which may result in an increase in intermodal noise.

[0034] In addition to the above ranges, the inventors have discovered that certain combinations of alpha parameter, maximum index percent difference, and core diameter are particularly beneficial. These include, but are not limited to, an alpha parameter of approximately 2, Δ=0.35-0.4%, and a core diameter of 14.0-16.0 μm; an alpha parameter of approximately 3, Δ=0.35-0.4%, and a core diameter of 12.0-15.0 μm; and an alpha parameter of approximately 4, Δ=0.30-0.4%, and a core diameter of 12.0-16.0 μm.

[0035] Properties of exemplary fibers designed in accordance with the present invention are listed in Table I along with properties of a standard SMF-28™ optical fiber, manufactured by Corning Incorporated. In this table, pin array bend loss and effective area (A_{eff}) were determined at a wavelength of 1550 nm.

Table I

	Δ (%)	Core Diameter (μm)	Dispersion @1525 (ps/nm-km)	Dispersion @1575 (ps/nm-km)	Cutoff λ_c (nm)	Cabled Cutoff (nm)	Pin array Bend loss (dB)	Aeff (μm^2)
2	.35	16.0	18.03	21.15	1236.4	1150	1.989	108.5
2	.40	14.7	17.58	20.70	1242.8	1145	0.638	94.6
3	.35	14.0	18.05	21.13	1231.9	1131	1.299	101.6
3	.40	13.0	17.68	20.74	1235.8	1125	0.365	88.4
4	.30	14.5	18.59	21.68	1223.8	1145	3.192	117.7
4	.35	13.4	18.32	21.38	1226.3	1144	0.830	100.7
4	.40	12.5	18.02	21.07	1228.9	1142	0.203	87.8
20 SMF28™	.35	9.0	15.61	18.49	1253.7	959	4.350	81.5

[0036] For each fiber the dispersion was measured at 1525 nm and 1575 nm and the dispersion slope calculated from these points. Using the dispersion slope, the dispersion curve was extrapolated to determine the zero dispersion wavelength λ_o (the wavelength at which the dispersion goes to zero). Cut off wavelength of the fiber was measured. As can be seen from Table I, fibers made according to the invention have cut off wavelengths λ_c between 1220 nm and 1250 nm. At the fiber cutoff wavelength λ_c, the fiber transitions from multimode to single mode. In actual applications, fibers generally are packaged in fiber optic cables. Cabling changes the cutoff wavelength. Generally, cabling lowers the cutoff wavelength between 50 nm to 400 nm, depending on the type of fiber. In the type of fibers disclosed in Table I, cabling lowers the cutoff wavelength between 50 nm and 100 nm. As shown in Table I, the cabled cutoff wavelengths of the fibers produced in accordance with the present invention are between 1125 nm and 1150 nm. Thus, all of those fibers are capable of multimode operation at 850 nm and single mode operation at 1300 nm in either uncabled or cabled configuration.

[0037] Attenuation induced in a fiber by bending can be measured as pin array bend loss. To determine pin array bend loss, attenuation is measured for a fiber configured to have essentially no induced bending loss. The fiber is then woven in a serpentine path through a pin array. The pin array is a set of ten cylindrical pins arranged in a single row and held in a fixed vertical position on a flat surface. The pin spacing is 5 mm, center to center, and the pin diameter is 0.67 mm. During testing, sufficient tension is applied to make the serpentine woven fiber conform to the portions of the pin surface at which there is contact between fiber and pin. Attenuation of the fiber in the pin array is then measured.

[0038] The pin array bend loss is the difference between the two measured attenuation values expressed in dB. All of the fibers shown in Table I that were designed in accordance with the present invention have lower pin array bend loss than the standard SMF-28™ optical fiber manufactured by Corning Incorporated. In fact, the pin array bend losses are as low as 1/20 the pin array bend loss of the standard SMF-28™ optical fiber.

[0039] The effective area (A_{eff}) is generally defined as,

$$A_{eff} = \frac{2\pi\left(\int_0^\infty |E|^2 r dr\right)^2}{\int_0^\infty |E|^4 r dr}$$

where E is the electric field associated with the propagated light and r is the radial distance from the center axis of the fiber. A larger effective area is beneficial because it results in a lower power density across the fiber, improving fiber performance. The improved performance includes reduced nonlinear effects and lower splicing and connecting loss.

[0040] All of the fibers shown in Table I that were designed as disclosed herein have larger effective areas than the standard commercially available single mode fiber designed for use at a wavelength near 1300 nm, for example Corning's SMF-28™ fiber. For example, the first listed fiber has an effective area (Aeff) that is approximately 33% higher than the standard SMF-28™ fiber (108.5 μm^2 versus 81.5 μm^2).

[0041] In addition to the data in Table I, the bandwidths of these fibers were calculated via computer simulation. All of the fibers were found to have bandwidths of at least approximately 0.6 GHz.km at 850 nm in multimode operation, some having 850 nm bandwidth greater than 1.0 GHz.km.

[0042] Further, the inventors have discovered that intermodal noise can be reduced by designing a fiber having a λ_p offset from the desired operating wavelength λ_{op}. In this configuration, the average difference between group time delays of the modes in multimode operation is sufficiently greater than zero to provide reduced intermodal noise. What constitutes a sufficient difference is discussed below.

[0043] The operating wavelength λ_{op} is the wavelength at which the fiber is intended to be used. The peak bandwidth wavelength λ_p is the wavelength at which equalization of the group time delays occur, i.e., the sum of the group time delay differences of all the modes propagating in a multimode fiber are nearly equal to zero. In the ideal case, the group time delay difference of the modes is zero at λ_p which corresponds to a bandwidth which is large without bound. In practice, the bandwidth versus wavelength curve exhibits a large but finite value of bandwidth at wavelength λ_p. At equalization, the fiber has its highest bandwidth. However, there is a significant amount of intermodal noise when the operating wavelength λ_{op} is at the peak bandwidth wavelength λ_p. Thus, operating at the peak wavelength results in a noisy signal while operating at any other wavelength results in a decrease in bandwidth. By designing a fiber with a sufficiently large difference between the operating wavelength and peak wavelength, λ_{op}-λ_p, the average difference between group time delays of the modes in multimode operation is sufficiently greater than zero, to provide an optimum configuration in which bandwidth is as high as possible because intermodal noise has been limited. The bandwidth is effectively optimized by selecting refractive index profile parameters that move λ_p away from λ_{op}. The reduction in bandwidth due to operating away from λ_p is more than made up by the increase in bandwidth due to the reduction in intermodal noise.

[0044] Design parameters to overcome intermodal noise, that is the parameters to offset λ_p from λ_{op} by a desired amount, can be determined by calculation and then implemented in a fiber. The case for a 2-mode fiber is discussed below. Similar derivations have been developed for the general N-mode fiber as is discussed below.

[0045] In a 2-mode fiber, the optical phase difference between the lowest order modes, LP_{11} and LP_{01}, can result in optical interference. As discussed previously, external perturbations, such as changes in temperature and mechanical distortions, can produce such phase differences which can result in optical interference and thus changes in the output optical intensity at a given transverse position on the output end of the fiber as a function of time. This modal interference condition, which varies in time, creates an intensity variation in the modal pattern, i.e., modal noise.

[0046] The external perturbations affect the group time delay, τ. Equalization of the group time delay of the LP_{11} and LP_{01} waveguide modes occurs when $\Delta\tau = \tau(01) - \tau(11) = 0$. In other words, the time it takes for both modes to travel the length of the fiber is the same. As disclosed herein, a preferred embodiment of an optical fiber has an alpha parameter selected to nearly equalize mode group delay time. Sufficient difference in mode group time delay is maintained to limit intermodal noise. A number of factors, including index perturbations in the fiber, can modify the optimum alpha parameter for equalization. Thus, optimum alpha parameter is defined by a range. Fibers designed in accordance with these embodiments have an alpha parameter in the range of approximately 2 to approximately 8. More preferably, alpha parameter is in the range of approximately 2 to approximately 4. More preferably still, alpha parameter is in the range of approximately 2 to 3.3 with a preferred narrower range 2.5 to 3.0.

Referring to Figure 13, an example is shown of the dependence of optimum alpha (α) parameter on wavelength for the case of a 2-mode fiber. By optimum parameter is meant the value of of core refractive index profile that provides maximum bandwidth. Thus, an examination of curve 102 in Figure 13 shows that for the values of Δ% and diameter of the core selected (see below), an of 2.5 provides a λ_p of 0.75 μm, a wavelength that can be desirable in a system having an operating wavelength λ_{op} of 0.85 μm, for example. In the operating wavelength range from about 0.75 μm to 1.0 μm, curve 102 shows corresponding optimum values in the range from about 2.5 to 4. For a wavelength of about 850 nm, optimum alpha parameter is seen to be in the range 2.5 to 3.5. Curve 102 is representative of the core configuration in which Δ% is about 0.3% and core diameter is about 12 μm. For comparison purposes, curve 104 is included in Figure 13. Curve 104 is representative of the same core configuration as that of curve 102 except that the refractive index profile exhibits a depression on the centerline of the fiber. The root mean square width of the depression is about 0.1 μm and has a minimum relative refractive index percent of about zero. The presence of the centerline depression lowers the optimum alpha parameter, particularly at longer wavelengths.

[0047] Preferably, the fiber disclosed is designed so that $\Delta\tau$ is not 0 at the operating wavelength λ_{op}. In other words, the peak bandwidth wavelength λ_p for time delay equalization is purposely offset in wavelength from the operating wavelength λ_{op}. The subsequent reduction in bandwidth is not severe, and allows a significant reduction in the intermodal noise. This reduction is due to coherence damping which depends on the source spectral width and the fiber propagation characteristics.

[0048] Both actual testing and mathematical simulations were conducted. Actual testing was conducted using the apparatus 2 illustrated in Figure 1. The apparatus 2 includes a white light source 10, a 20 m long SMF-28™ optical fiber 20 (single mode at wavelength greater than about 1300 nm) having a joint region 25, a 2-mode fiber 40 fabricated as disclosed herein having a joint region 45 and an optical analyzer 50. Holding the joint regions 25 of the single mode fiber 20 and the joint region 45 of the 2-mode fiber 40 is an XYZ micro-positioner 35.

[0049] Figures 2A and 2B illustrate alternative fiber alignments used to test the 2-mode fiber fabricated as disclosed herein. With the micro-positioner 35, the joint regions 25 of the single mode fiber 20 and the joint region 45 of the 2-mode fiber 40 can be aligned as in Figure 2A or offset as in Figure 2B. If the fibers are aligned as in Figure 2A, only the LP_{01} mode is present in the 2-mode fiber 40. However, if the fibers are offset as in Figure 2B, both the LP_{01} and LP_{11} modes are present in the 2-mode fiber 40.

[0050] Fiber designs and simulations were generated based on the following general equation for the speckle constant, γ (the standard deviation of the optical power fluctuations caused by optical interference among the modes of a multimode fiber),

$$\gamma^2 = \frac{\sigma^2}{\langle I \rangle^2} = \frac{\left(\langle I^2 \rangle - \langle I \rangle^2\right)}{\langle I \rangle^2}$$

where is the standard deviation for variations in optical intensity I and $\langle I \rangle$ is the average value of the optical intensity. For the two mode case, this equation simplifies to,

$$\gamma^2 = \frac{A}{I_0^2} + \frac{B}{I_0^2}\cos(2\pi\nu_0\Delta\tau)\exp\left[-(2\pi\sigma_s\Delta\tau)^2\right]$$

where A and B are adjustable parameters, ν_0 is the optical frequency, $_s$ is a measure of the source spectral width, I_0 is the source intensity amplitude and $\Delta\tau$ is the normalized group delay time difference between modes (normalized per kilometer).

One can derive an expression for the speckle constant for the general N-mode case using the relation, $\gamma^2 = \int C_p(\nu)\left|\overrightarrow{h(\nu)}\right|^2 d\nu$, where $C_p(\nu)$ is the source spectral intensity and $\overrightarrow{h(\nu)}$ is the impulse response function. A satisfactory evaluation of the speckle constant can be made by making a Gaussian approximation for $C_p(\nu)$ and expanding $\overrightarrow{h(\nu)}$ in a Fourier series, both techniques being known in the art. The discussion of the two-mode case applies equally well to the N-mode case.

[0051] Under actual operating conditions, the second term of the two mode equation dominates. This term includes an oscillatory (cosine) term and, more importantly, an exponential decay term. The inventors have discovered that intermodal noise can be reduced as the magnitude of the argument of the exponential term increases. Preferably, the argument is at least approximately -1. More preferably, the argument is between approximately -1 and approximately -3. By increasing the argument in this manner, the intermodal noise can be significantly reduced. That is, the noise can be reduced to a level satisfactory for commercial use. In particular, the intermodal noise is made to be less than 0.5 dB. Preferably, the intermodal noise is made to be less than 0.25 dB.

[0052] For an N-mode fiber, $\Delta\tau$ is summed over all N modes. This calculation has been done to give an expression including the optimum alpha parameter in an equation including the group index N_1, fiber length L, speed of light c, relative index Δ, and the number of modes corresponding to a particular alpha profile N( ). An operative equation for the N-mode case is, $\left| \frac{N_1 L}{c} \left(\Delta(+/-\delta\alpha) \middle/ \alpha_{op}+2 \right) \left(1 \middle/ N(\alpha_{op}) \right)^{\alpha_{op}/\alpha_{op}+2} \otimes 2\pi\sigma_s \right| \geq 1$.

Given the index profile of the fiber and the operating wavelength, some of the group times delays may be positive while others may be negative relative to a reference time delay (the reference time delay is the travel time of light propagating at λ_p over the particular length of fiber) for propagation at the operating wavelength. Note, if all of the group delay differences are either all negative or all positive, the absolute value of the sum is always greater than zero, a preferred condition.

[0053] Two-mode fibers were designed and simulations conducted based on the two mode equation above. A comparison of the simulation, curve 52, with actual data, curve 54, is illustrated in Figure 3. The actual data were collected from a fiber having a peak modal bandwidth wavelength λ_p of approximately 770 nm and an operating wavelength λ_{op} of 850 nm. The decreasing intensity portion of the curve, 53, is indicative of the cut off wavelength for the third mode, that is, the wavelength above which the fiber supports two modes. The 2-mode fiber length was approximately 5 meters and had a measured bandwidth of 1.3 GHz-km at 850 nm. In Figure 3, the simulated data has been offset from the actual data for clarity. The simulation was done using a wavelength data point spacing of 0.5 nm, a λ_p of 770 nm, and a full width half maximum (FWHM) spectral width of the source of 2 nm. As can be seen by comparing curves 52 and 54, the simulation is a very good match for the actual fiber data. Further, both the actual data and the simulation clearly illustrate that in a fiber fabricated according to this aspect of the invention, the intensity modulation with wavelength caused by aliased detection of the optical interference between modes is directly related to intermodal noise 47. This intermodal noise 47 is centered around the peak wavelength and decays dramatically at the operational wavelength, 850 nm.

[0054] The decay of the spectral modulation or "coherence damping" is dependant on the linewidth of the light source. The more monochromatic the light, the more slowly the damping. Thus, a longer fiber length is required to ensure sufficient damping of intermodal noise at the end of the fiber. This is illustrated in Figure 4. In this figure, simulated coherence damping curves for a 3 meter fiber length are compared. The damping curves 55, 56, and 57 were calculated using a wavelength data point spacing of 1.0 nm. The damping curve depends upon the FWHM source spectral width as can be seen by comparing curve 55 illustrative of damping for a 0.02 nm source spectral width, to curves 56 and 57, illustrative of damping for 0.2 nm and 2.0 nm spectral width, respectively. As can be seen in Figure 4, very coherent, narrow spectral width light sources display little damping in short lengths of fiber.

[0055] Figures 5-12 illustrate simulated spectra for fibers of lengths varying from 10 meters to 5 kilometers. All of these spectra were generated with a peak wavelength of 770 nm, a data point spacing of 0.5 nm, and a FWHM source with a spectral width of 0.40 nm. The longer the fiber, the more quickly the intermodal noise attenuates as a function of wavelength. Thus, for long lengths of fiber, it is possible to design and operate a fiber with a peak wavelength closer to the actual operating wavelength. In the figures, λ_{op} is taken to be 850 nm. Curve 58 in figure 5, calculated for a 10 m fiber length shows modal noise level at the operation wavelength 59 to be about 0.5 dB. Bandwidth in this example is above about 0.6 GHz.km. Curve 60 in figure 6, calculated for a 20 m length of fiber shows modal noise near zero at operating wavelength 61. Bandwidth is greater than 0.6 GHz.km but less than 1.3 GHz.km. Likewise curve 62 in figure 7, calculated for fiber length of 50 m, shows modal noise of zero at operating wavelength 61. The same is true for curve 63 in figure 8 calculated for 100 m fiber length, curve 64 in figure 9 calculated for 500 m fiber length, curve 65 in figure 10, calculated for a 1000 m fiber length, curve 66 in figure 11 calculated for a 2000 m length, and curve 67 in figure 12 calculated for a 5000 m length. As fiber length increases, coherence damping increases, thus narrowing the width of the intermodal noise. Curve 67 in figure 12 shows essentially no intermodal noise.

[0056] Further, the inventors have determined that longer fibers fabricated as disclosed herein allow the use of operating wavelengths λ_{op} closer to the peak wavelength λ_p. Thus, with the use of longer fibers, one can achieve very high bandwidths with little intermodal noise. Combinations of fiber length and peak separation which the inventors have found to be particularly advantageous include, 10-20 m with the absolute value of the difference between λ_{op} and λ_p of approximately 80 to approximately 150 nm (bandwidth 0.6-1.2 GHz.km); 20-100 m with the absolute value of the difference between λ_{op} and λ_p of approximately 12 to approximately 80 nm (bandwidth 1.2-7 GHz.km); 100-1000 m with the absolute value of the difference between λ_{op} and λ_p of approximately 2 to approximately 12 nm (bandwidth 2-13 GHz.km); greater than1000 m with the absolute value of the difference between λ_{op} and λ_p of approximately 0 to approximately 2 nm (bandwidth at least 3 GHz.km and preferably greater than 13 GHz.km). These results are summarized in Table II below for a fiber designed for operation at 850 nm as discussed above. The refractive index profile parameters can correspond to any of those set forth in Table 1.

Table II

Fiber length (m)	λ_{op}-λ_p (nm)	Bandwidth (GHz.km)
10-20	80-150	0.6-1.2
20-100	12-80	1.2-7
100-1000	2-12	7-13
> 1000	0-2	> 13

[0057] The foregoing description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the invention. The drawings and description were chosen in order to explain the principles of the invention and its practical application. It is intended that the scope of the invention be defined by the claims appended hereto, and their equivalents.

WHAT IS CLAIMED IS:

1. An optical fiber, comprising:

a core and a cladding, said core having a refractive index profile including an alpha profile with an alpha parameter in the range of approximately 2 to approximately 8, a maximum refractive index percent difference between the core and a cladding in the range of approximately 0.26% to approximately 0.5% and a core diameter in the range of approximately 6.0 to approximately 16.0 μm;

wherein the optical fiber has a bandwidth of at least approximately 0.6 GHz.km at 850 nm and a cabled cut off wavelength in the range from about 1050 nm to 1300 nm.

2. The optical fiber of claim 1, wherein the core has a diameter in the range of approximately 6.0 to approximately 14.0 μm.

3. The optical fiber of claim 1, wherein a maximum refractive index percent difference between the core and the cladding is in the range of approximately 0.3% to approximately 0.4%.

4. The optical fiber of claim 1, wherein the core has an alpha parameter in the range from approximately 2 to approximately 4.

5. The optical fiber of claim 1, wherein the effective area is greater than 70 μm^2 at 1550 nm.

6. The optical fiber of claim 1, wherein the effective area is greater than 90 μm^2 at 1550 nm.

7. The optical fiber of claim 1, wherein the pin array bend loss is less than 4 dB at 1550 nm.

8. The optical fiber of claim 1, wherein the pin array bend loss is less than 2 dB at 1550 nm.

9. The optical fiber of claim 1, wherein the mode field diameter is greater than or equal to 10 μm at 1550 nm.

10. The optical fiber of claim 1, wherein an index profile of the core is configured in accordance with an operating wavelength, the bandwidth desired at the operating wavelength, and a length of the optical fiber.

11. The optical fiber of claim 10, wherein the index profile of the core is configured to have a peak modal bandwidth wavelength offset from the operating wavelength, the offset being sufficient to reduce intermodal noise.

12. The optical fiber of claim 1, wherein the alpha parameter is approximately 2, the maximum index percent difference between the core and the cladding is in the range from approximately 0.35% to approximately 0.4% and the core diameter is in the range from approximately 14.0 to approximately 16.0 μm, to provide a waveguide fiber having, at 1550 nm, effective area greater than 90 μm^2, and mode field diameter greater than 11 μm.

13. The optical fiber of claim 12, wherein pin array bend loss is less than 2 dB at 1550 nm.

14. The optical fiber of claim 1, wherein the alpha parameter is approximately 3, the maximum index percent difference between the core and the cladding is in the range of approximately 0.35% to approximately 0.4% and the core diameter is in the range of approximately 12.0 to approximately 15.0 μm, to provide a waveguide fiber having effective area greater than 85 μm^2, and mode field diameter greater than 10.5 μm.

15. The optical fiber of claim 14, wherein the pin array bend loss is less than 4 dB at 1550 nm.

16. The optical fiber of claim 1, wherein the alpha parameter is approximately 4, the maximum index percent difference between the core and the cladding is in the range from approximately 0.3% to approximately 0.4% and the core diameter is in the range from approximately 12.0 to approximately 16.0 μm, to provide a waveguide fiber having, at 1550 nm, an effective area greater than 85 μm^2, and mode field diameter greater than 10.5 μm.

17. The optical fiber of claim 16, wherein the pin array bend loss is less than 3.5 dB at 1550 nm.

18. An optical fiber, comprising:

a core; and

a cladding,

wherein the optical fiber is a multimode fiber at an operating wavelength and has a peak modal bandwidth wavelength offset from the operating wavelength and the offset is sufficient to substantially reduce intermodal noise at the operating wavelength.

19. The optical fiber of claim 18, wherein at the operating wavelength each mode has a group time delay and all of the group time delays are either all positive or negative, each of the group time delays being referenced relative to a lowest order mode (LP_{01} mode) associated with the optical fiber.

20. The optical fiber of claim 19, wherein at the operating wavelength each mode has a group time delay and the absolute value of the sum of the group time delay differences is greater than 0.

21. The optical fiber of claim 18, wherein the fiber is configured for multimode operation at a wavelength less than 1300 nm and single mode operation at a wavelength of at least approximately 1300 nm.

22. The optical fiber of claim 21, wherein a difference in a group time delay is either all positive or all negative for all modes in the multimode operation of the optical fiber, each of the group time delay being referenced relative to a lowest order mode (LP_{01} mode) associated with the optical fiber.

23. The optical fiber of claim 18, wherein the optical fiber is configured to have a bandwidth of at least approximately 0.6 GHz.km at 850 nm.

24. The optical fiber of claim 18, wherein the core has a diameter in the range of approximately 6.0 to approximately 16.0 μm and a maximum refractive index difference between the core and the cladding is in the range of approximately 0.3 to approximately 0.5%.

25. A method of designing an optical fiber having a bandwidth of at least 0.6 GHz.km at 850 nm in multimode operation and being in single mode operation at a wavelength of at least approximately 1300 nm, comprising the steps:

a) determining for a given length of optical fiber a minimum difference between the operating wavelength and a peak bandwidth wavelength such that the difference in the optical path lengths of the modes in multimode operation is greater than at least one coherence length associated with a source utilized to launch light into the optical fiber at the operating wavelength; and

b) determining a refractive index profile associated with the optical fiber in accordance with the minimum difference.

26. The method of claim 25, wherein determining a minimum difference includes calculating a speckle constant γ as a function of the bandwidth, a line width of the light, an intensity of the light, and the length of the optical fiber.

27. The method of claim 25, wherein determining a minimum difference includes having one of all positive or all negative differences in a group time delay for all modes of the multimode operation, the group time delay referenced relative to any of the modes of the multimode operation.

28. The method of claim 25, wherein determining a refractive index profile includes determining at least one of the operating wavelength, the bandwidth desired, and a length of the optical fiber during operation.

29. The method of claim 25, wherein determining a refractive index profile includes configuring an alpha parameter associated with the optical fiber in the range from approximately 2 to approximately 8.

30. The method of claim 25, wherein determining an index profile includes configuring an alpha parameter associated with the optical fiber in the range from approximately 2 to approximately 4.

31. The method of claim 25, wherein determining a refractive index profile includes configuring a maximum index difference in a core and a cladding of the optical fiber in the range from approximately 0.3 to approximately 0.5% and a diameter of a core of the optical fiber in the range from approximately 6 to approximately 16 μm.

32. An optical fiber system comprising:

an optical fiber having a core and a cladding and a length, said core having a refractive index profile including an alpha profile with an alpha parameter in the range from approximately 2 to approximately 8, a maximum refractive index percent difference between the core and the cladding in the range from approximately 0.3% to approximately 0.5% and a core diameter in the range from approximately 6.0 to approximately 16.0 μm;

a light source optically coupled to said fiber and having an operating wavelength, said optical fiber being multimode at the operating wavelength; wherein,

the alpha parameter, the maximum refractive index percent difference and the core diameter are selected to provide a peak bandwidth wavelength of said optical fiber that is offset from the operating wavelength by an amount sufficient to reduce intermodal noise at the operating wavelength.

33. The optical fiber of claim 32, wherein the length of the optical fiber is in the range of approximately 10 to approximately 20 m, an absolute value of the difference between the operating wavelength and the peak bandwidth wavelength is in the range of approximately 80 nm to approximately 150 nm, and the bandwidth is greater than approximately 0.6 GHz.km at the operating wavelength.

34. The optical fiber of claim 32, wherein the length of the optical fiber is in the range of approximately 20 m to approximately 100 m, an absolute value of the difference between the operating wavelength and the peak bandwidth wavelength is in the range of approximately 12 nm to approximately 80 nm, and the bandwidth is greater than approximately 1.2 GHz.km at the operating wavelength.

35. The optical fiber of claim 32, wherein the length of the optical fiber is in the range of approximately 100 to approximately 1000 m, an absolute value of the difference between the operating wavelength and

the peak bandwidth wavelength is in the range of approximately 2 to approximately 12 nm, and the bandwidth is greater than approximately 2 GHz.km at the operating wavelength.

36. The optical fiber of claim 32, wherein the length of the optical fiber is greater than 1000 m, an absolute value of the difference between the operating wavelength and the peak bandwidth wavelength is greater than zero and less than approximately 2 nm, and the bandwidth is greater than approximately 3 GHz.km at the operating wavelength.

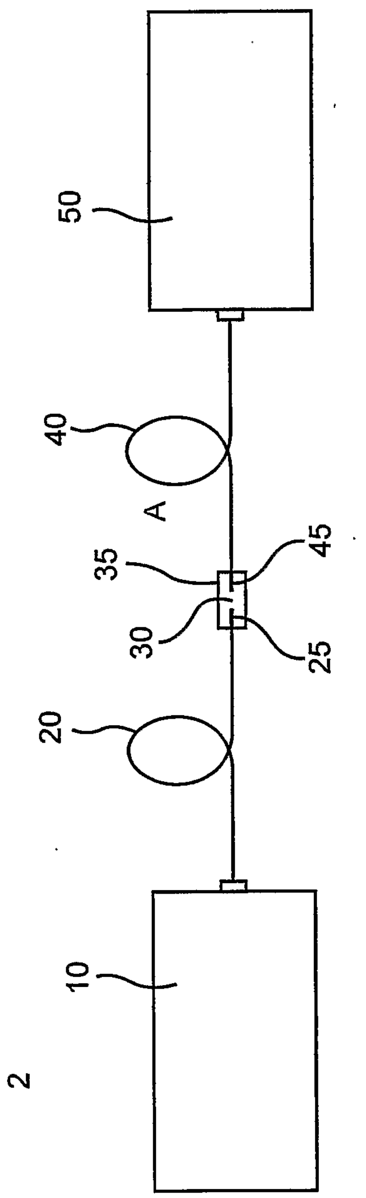


FIG. 1

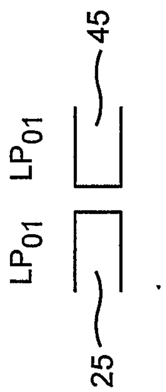


FIG. 2A

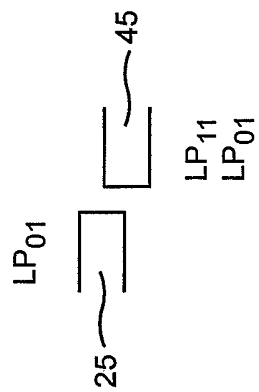


FIG. 2B

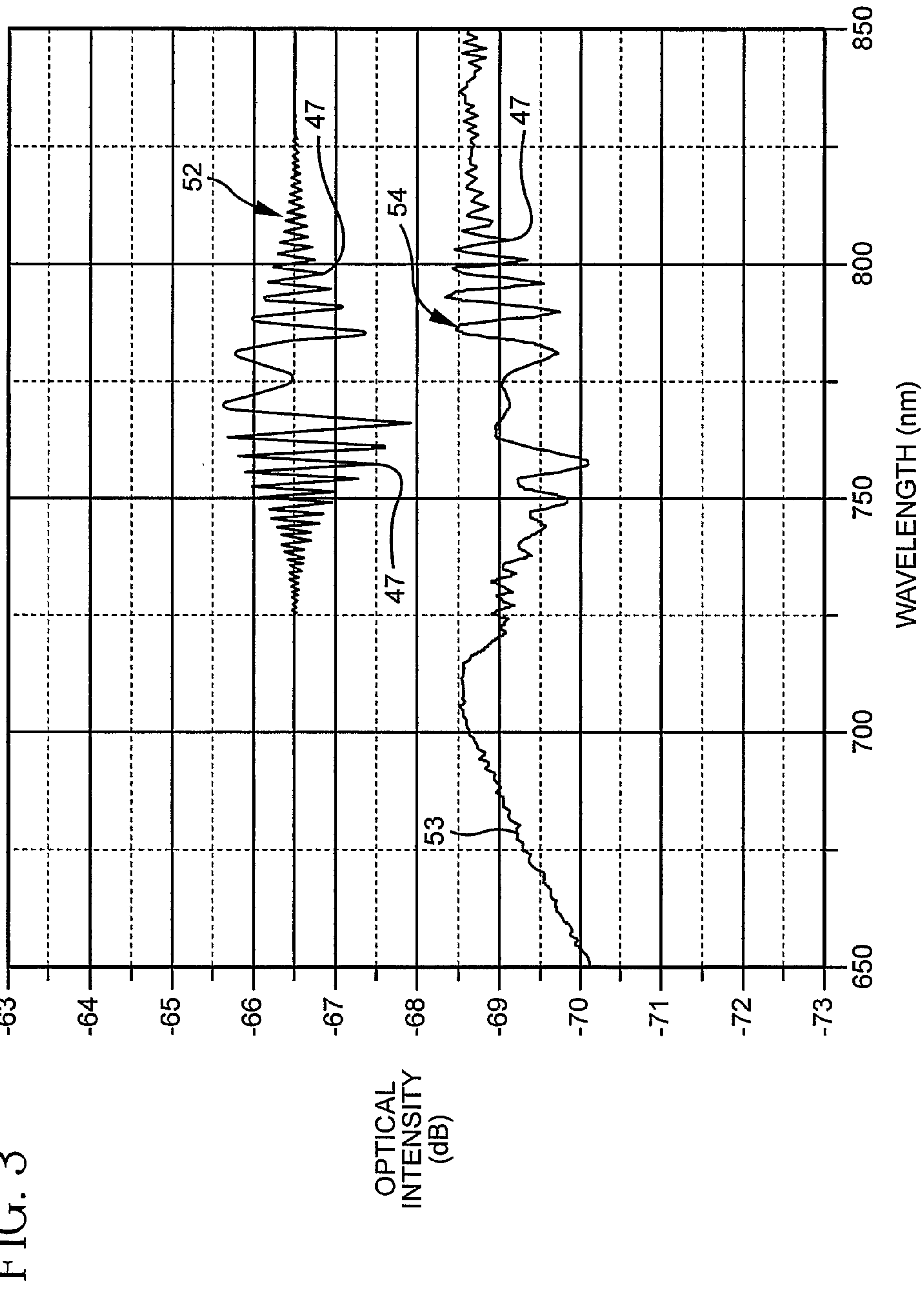

OPTICAL INTENSITY (dB)
-63
-64
-65
-66
-67
-68
-69
-70
-71
-72
-73
650
700
750
800
850
WAVELENGTH (nm)
52
47
54
47
47
53

FIG. 3

FIG. 4 COHERENCE DAMPING FOR VARIOUS SOURCE LINEWIDTHS

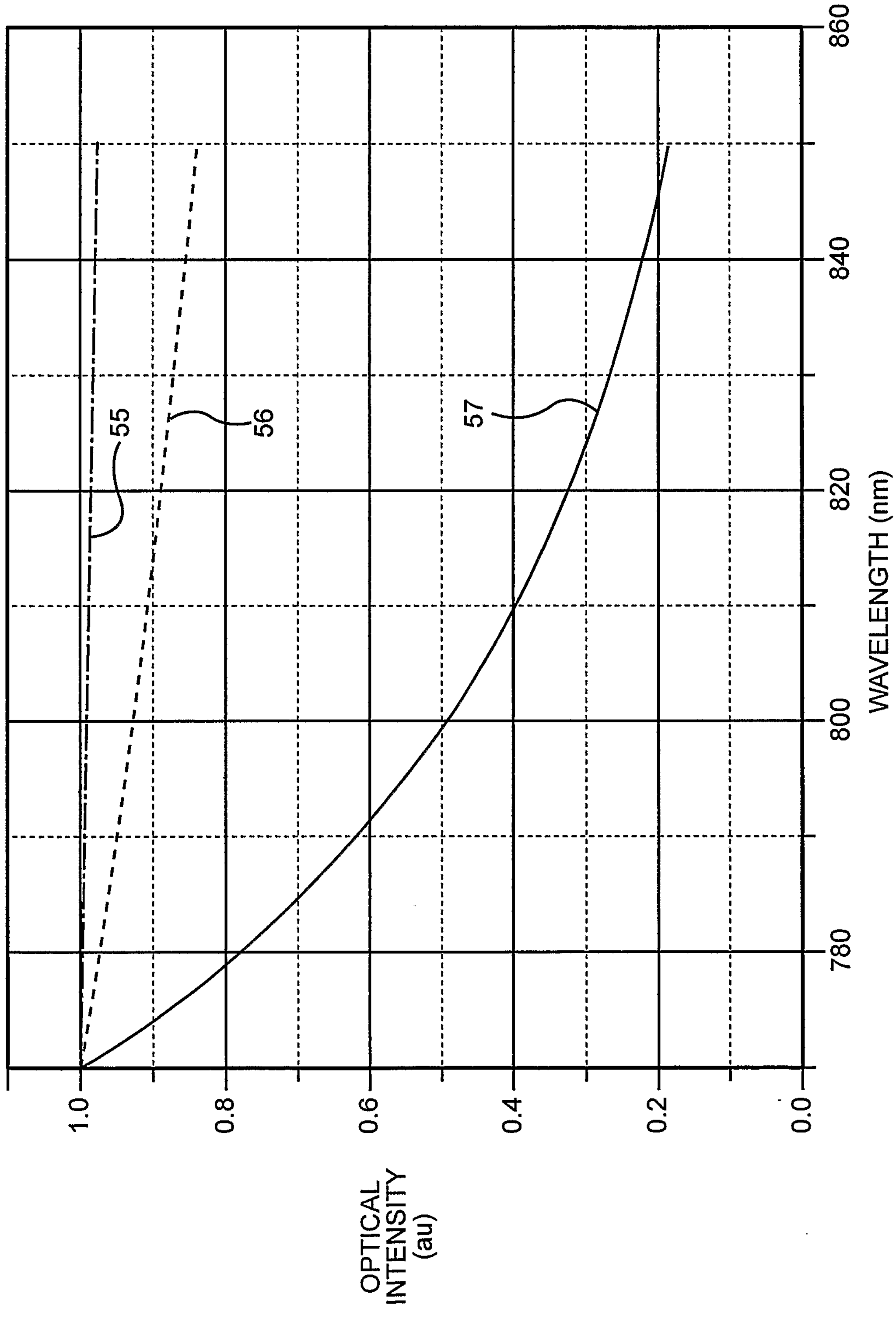


FIG. 5 SIMULATED SPECTRUM FOR OPTICAL FIBER LENGTH = 10 m

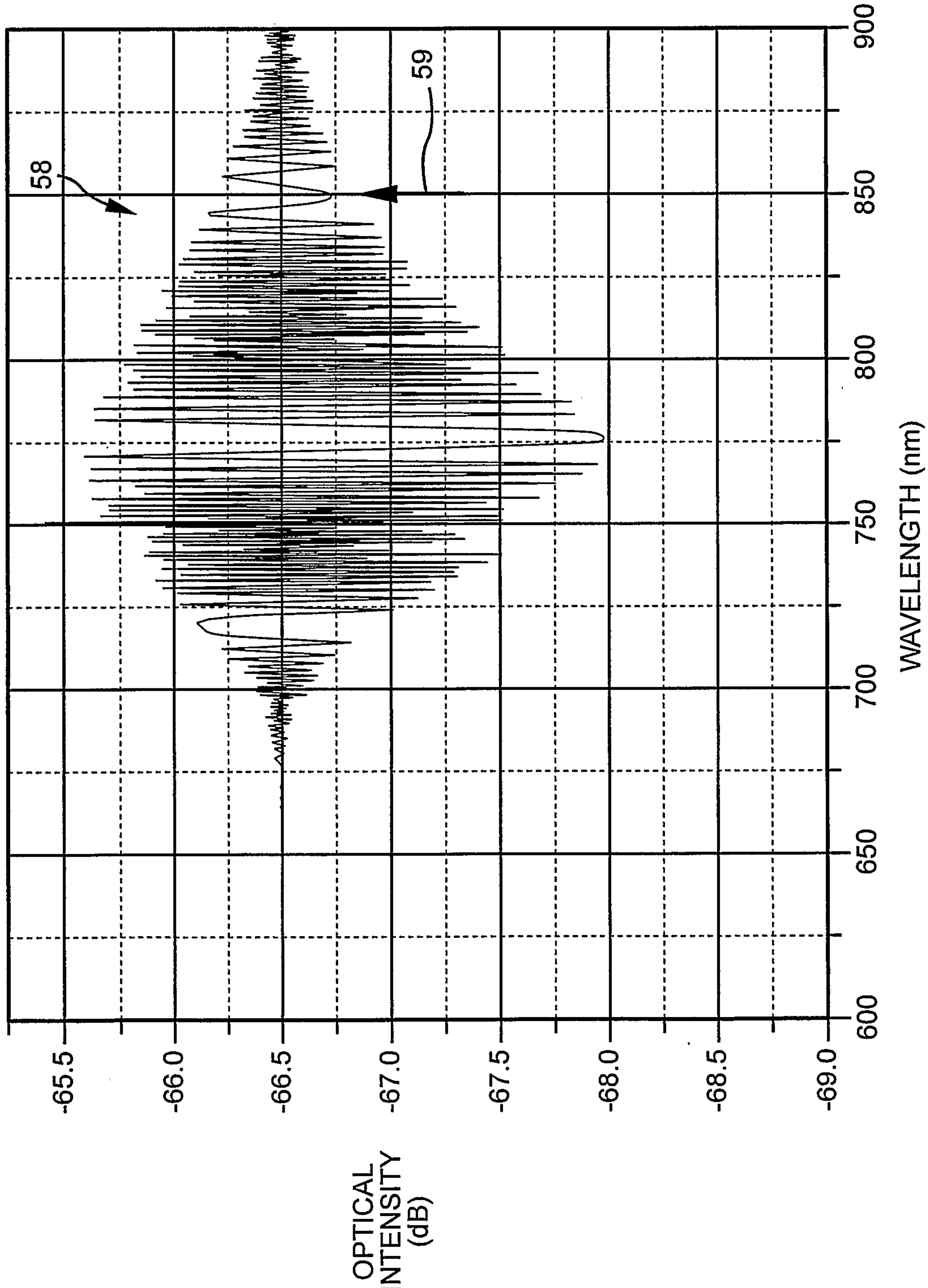


FIG. 6 SIMULATED SPECTRUM FOR OPTICAL FIBER LENGTH = 20 m

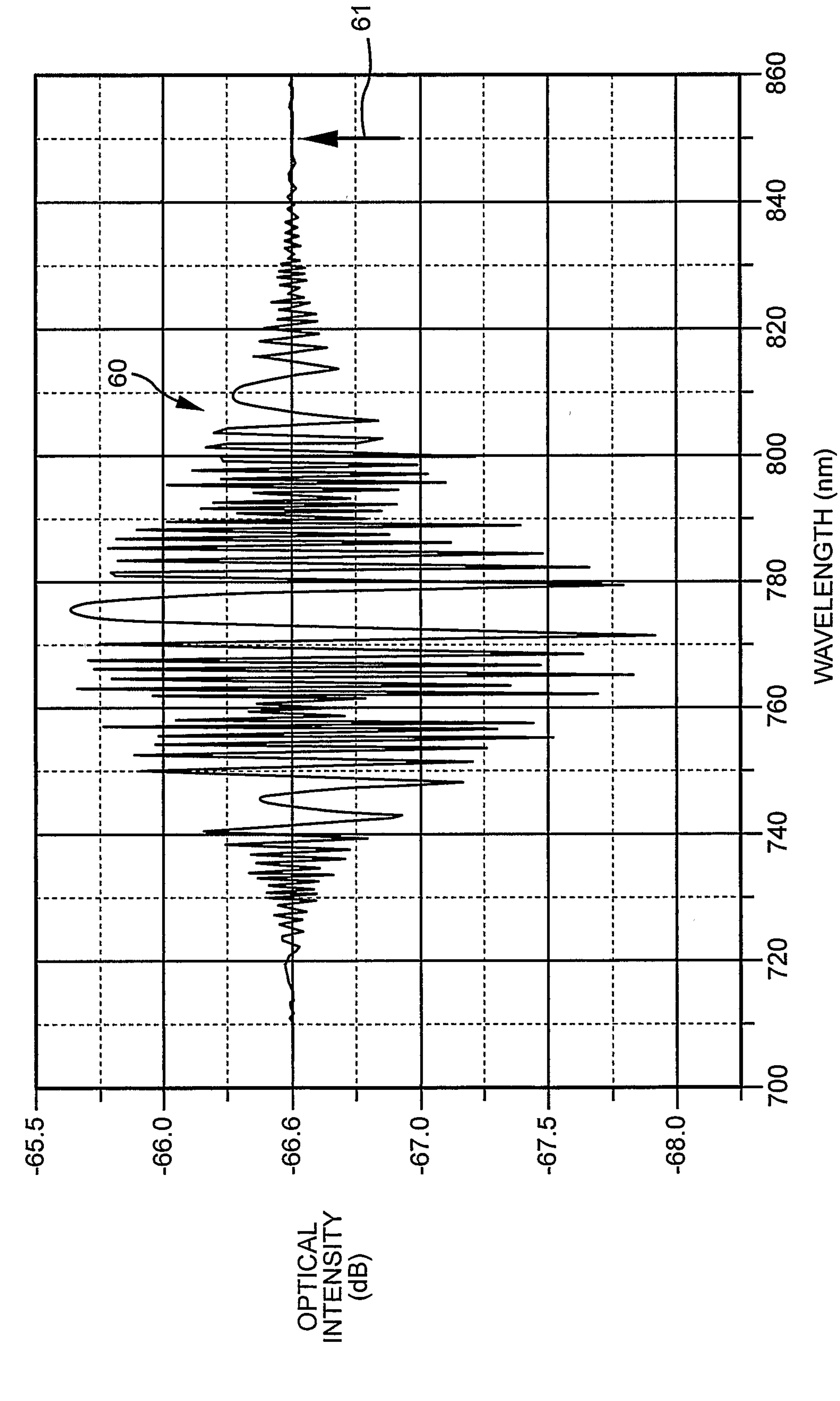


FIG. 7 SIMULATED SPECTRUM FOR OPTICAL FIBER LENGTH = 50 m

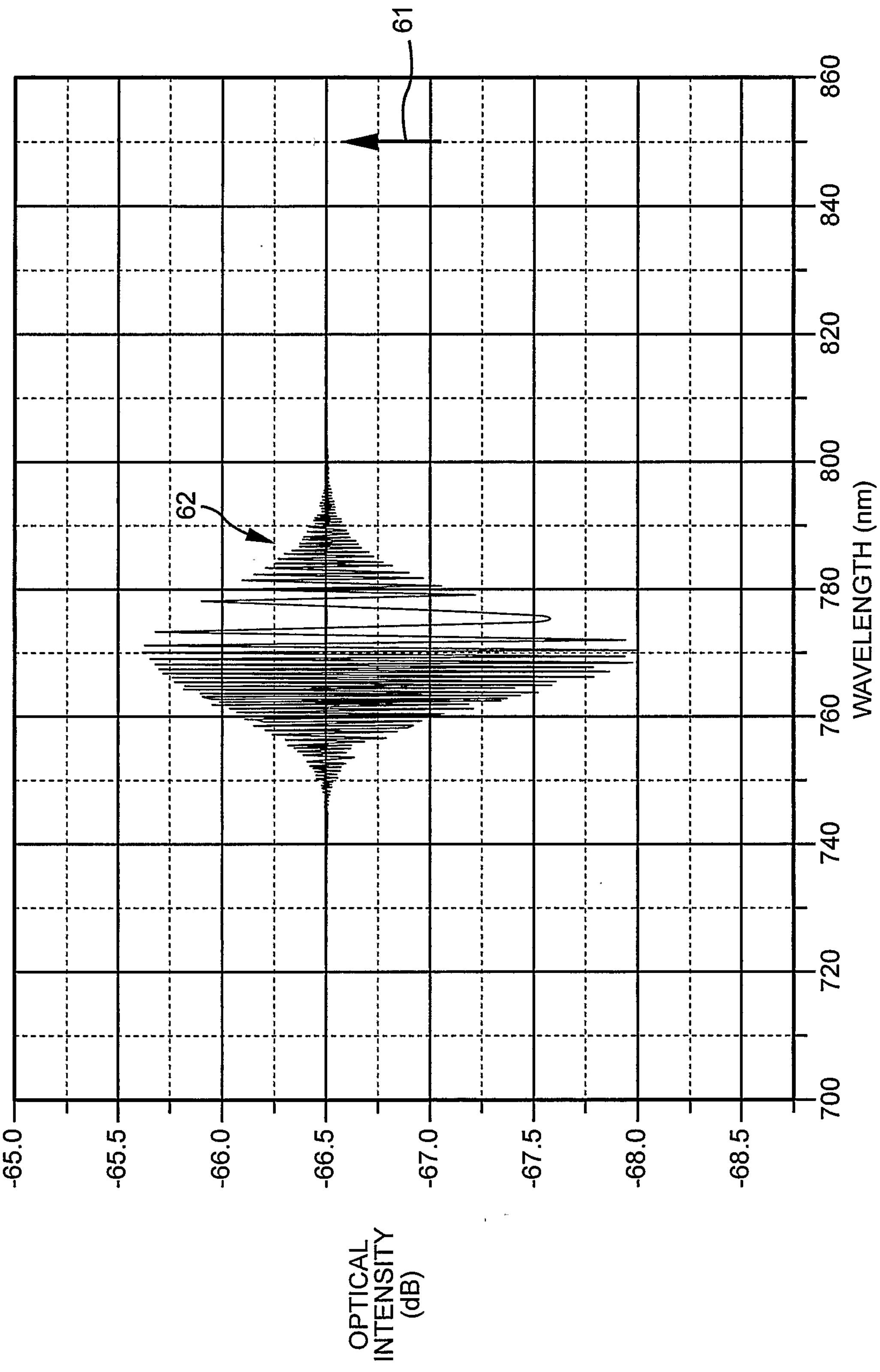


FIG. 8 SIMULATED SPECTRUM FOR OPTICAL FIBER LENGTH = 100 m

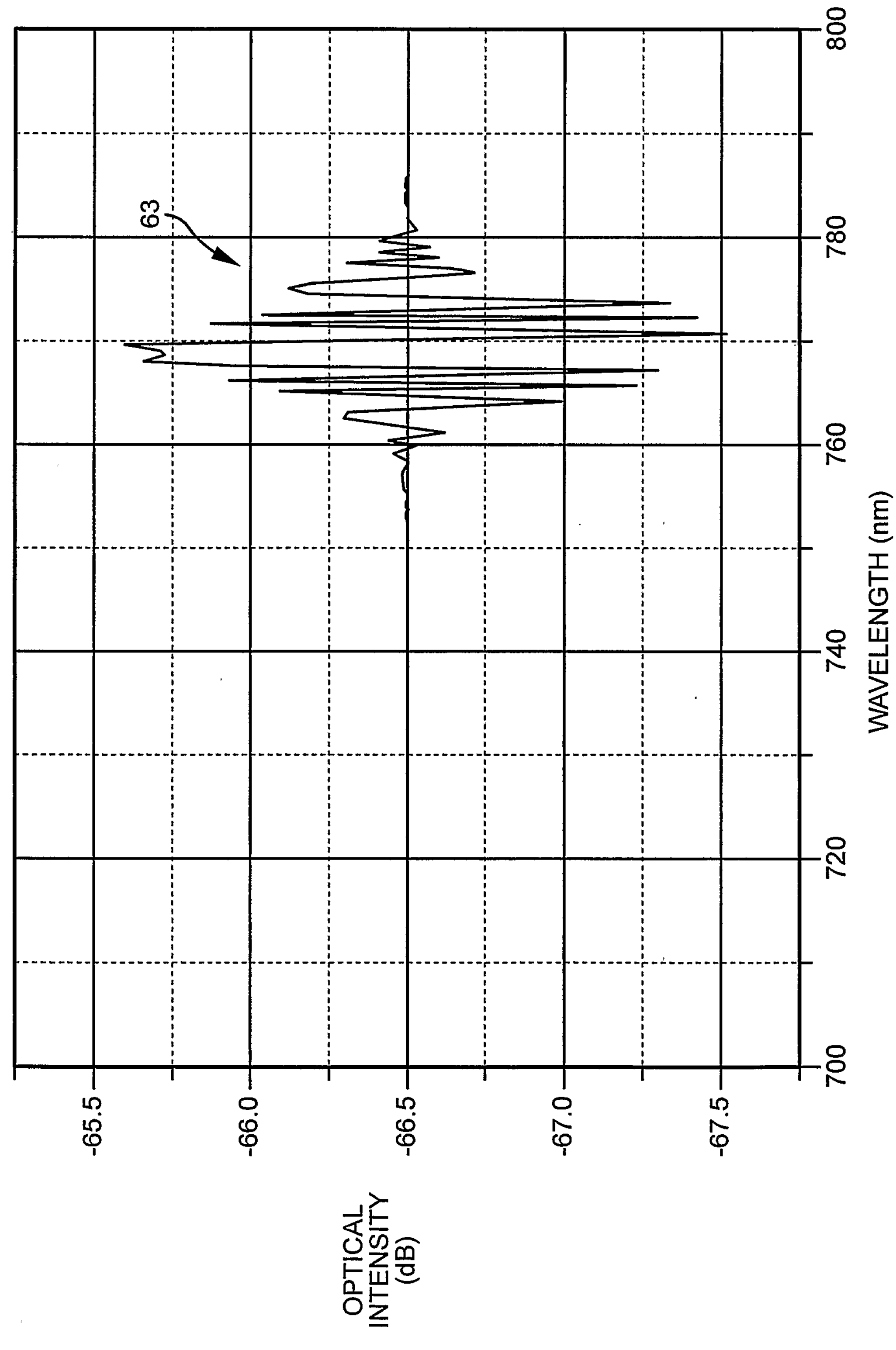


FIG. 9 SIMULATED SPECTRUM FOR OPTICAL FIBER LENGTH = 500 m

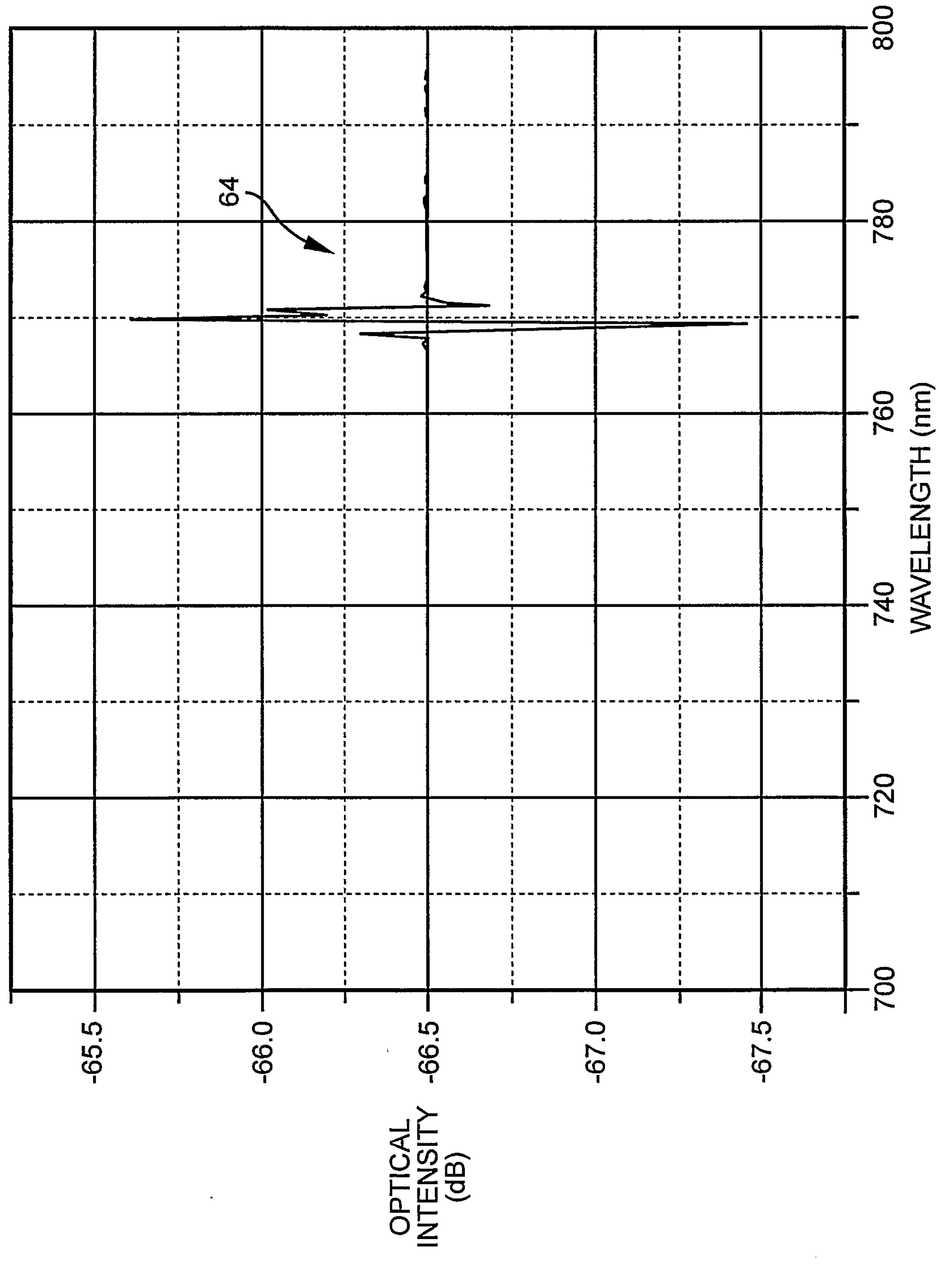


FIG. 10 SIMULATED SPECTRUM FOR OPTICAL FIBER LENGTH = 1000 m

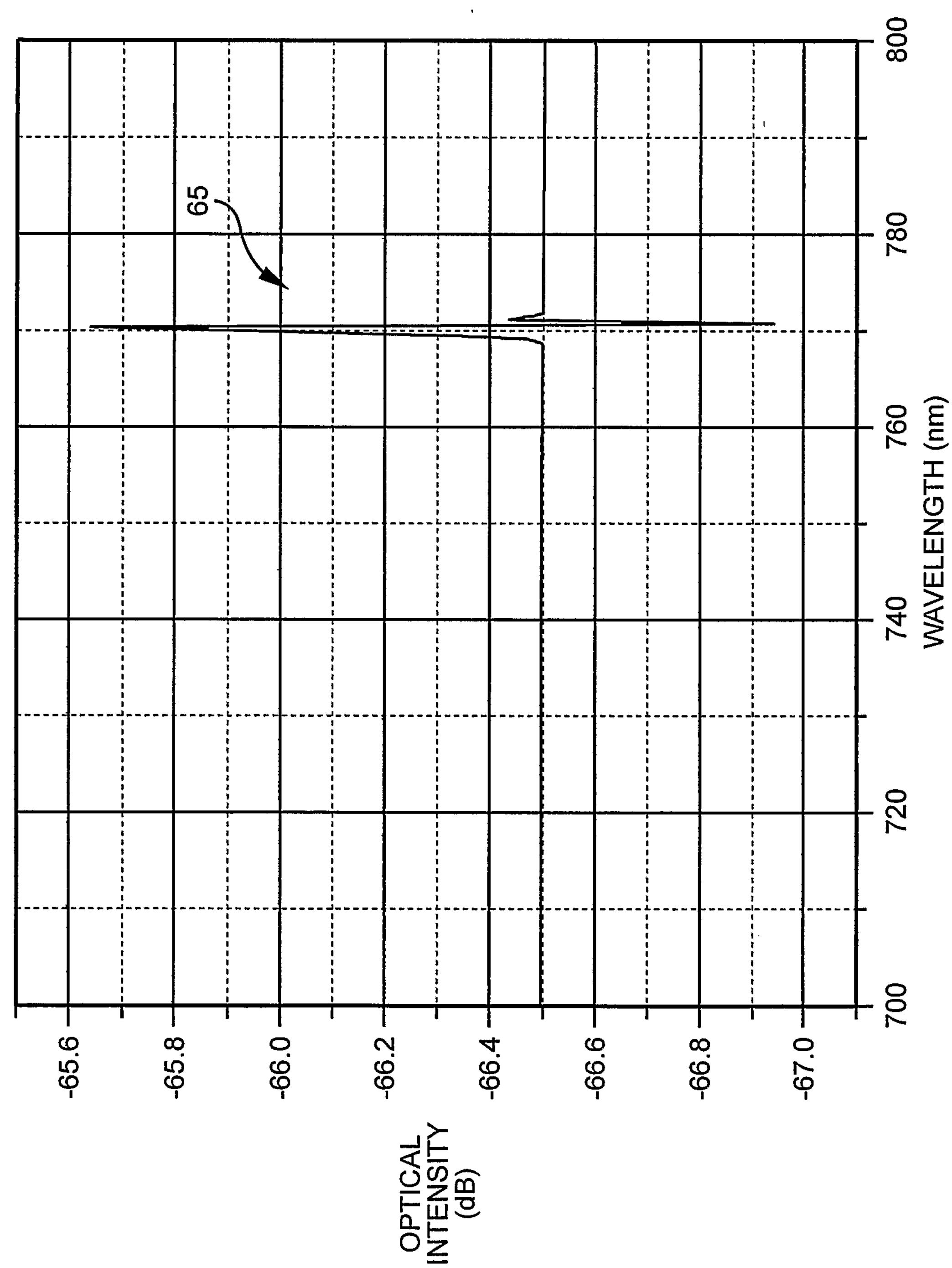


FIG. 11

SIMULATED SPECTRUM FOR OPTICAL FIBER LENGTH = 2000 m

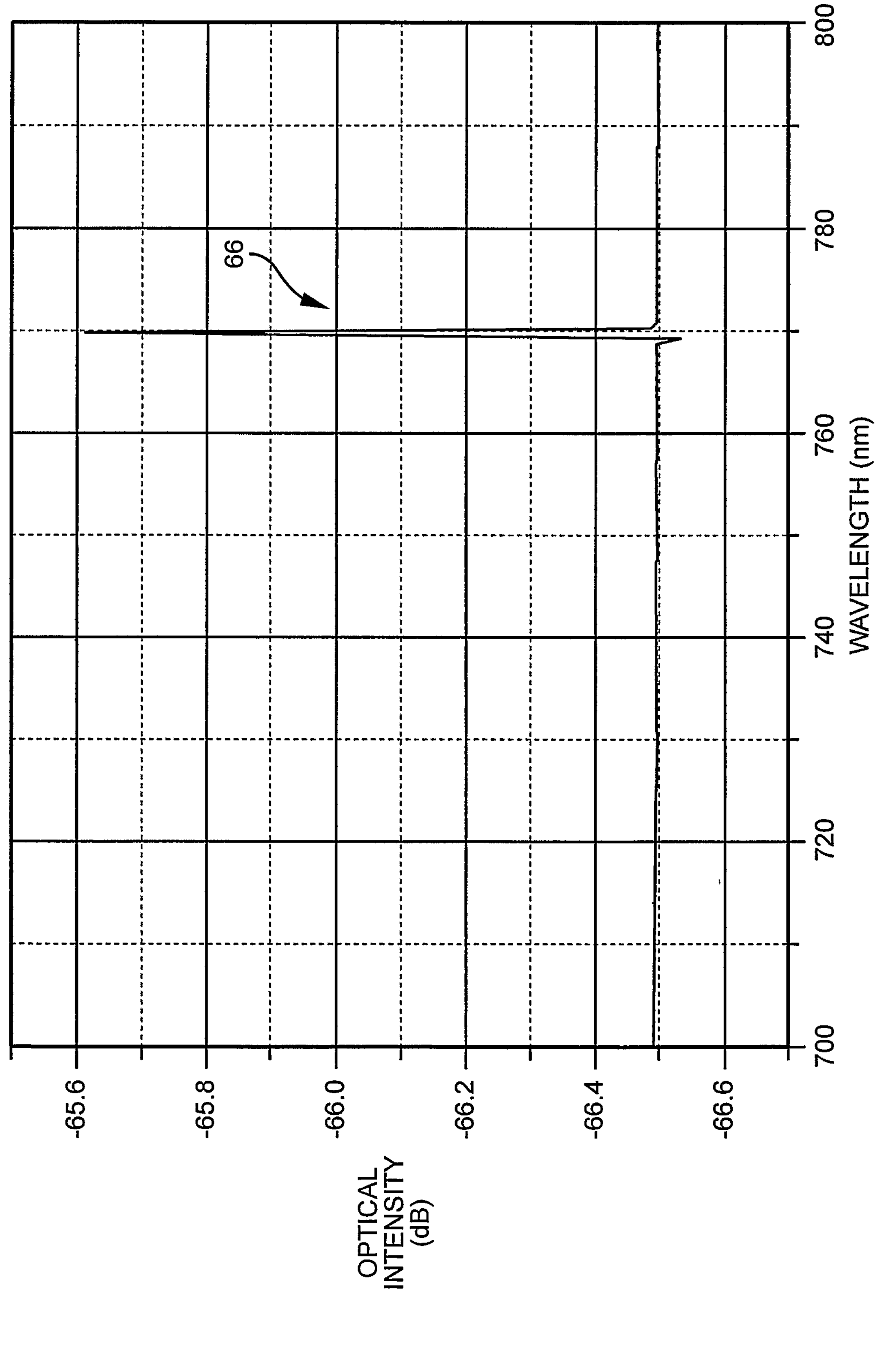
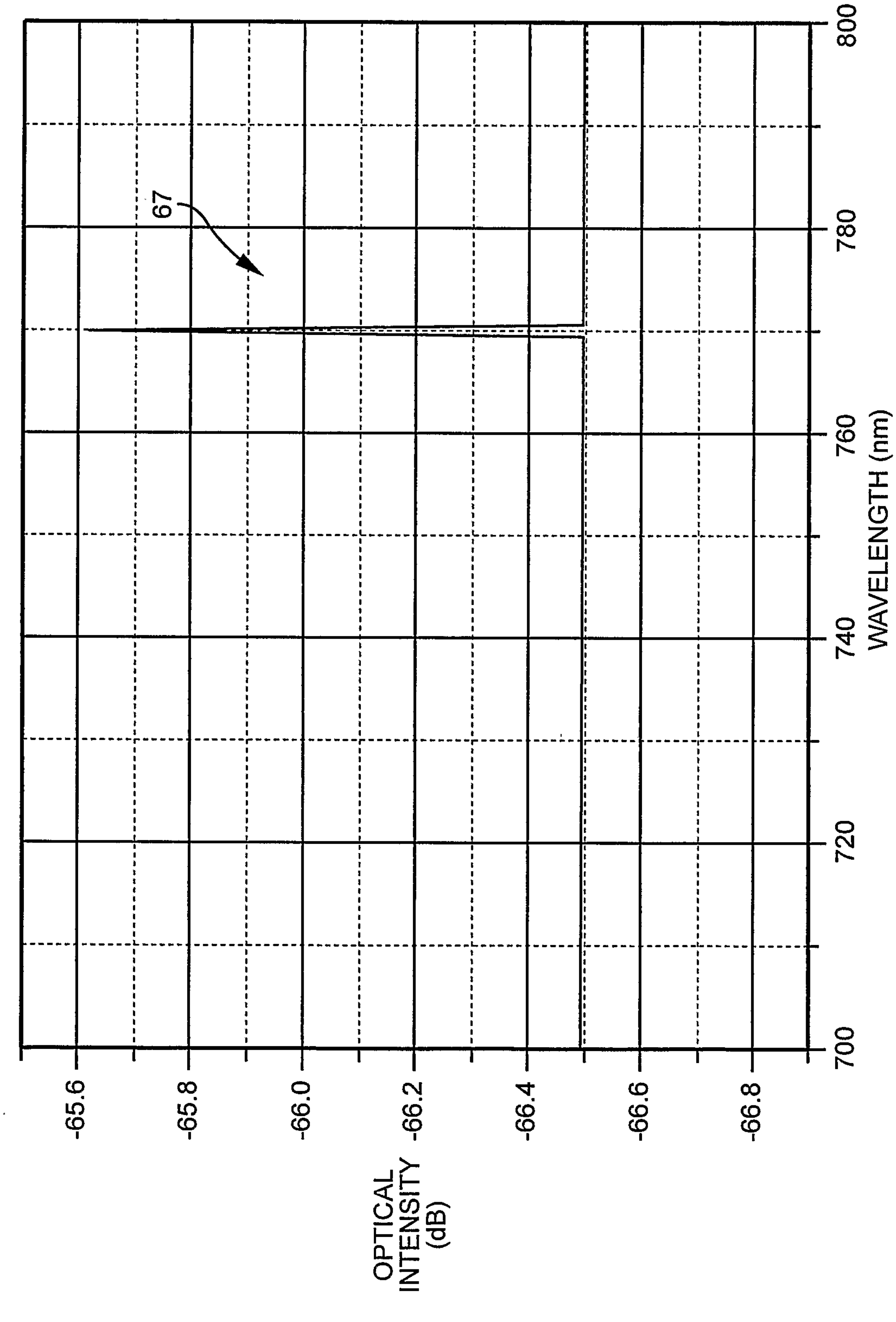


FIG. 12

SIMULATED SPECTRUM FOR OPTICAL FIBER LENGTH = 5000 m



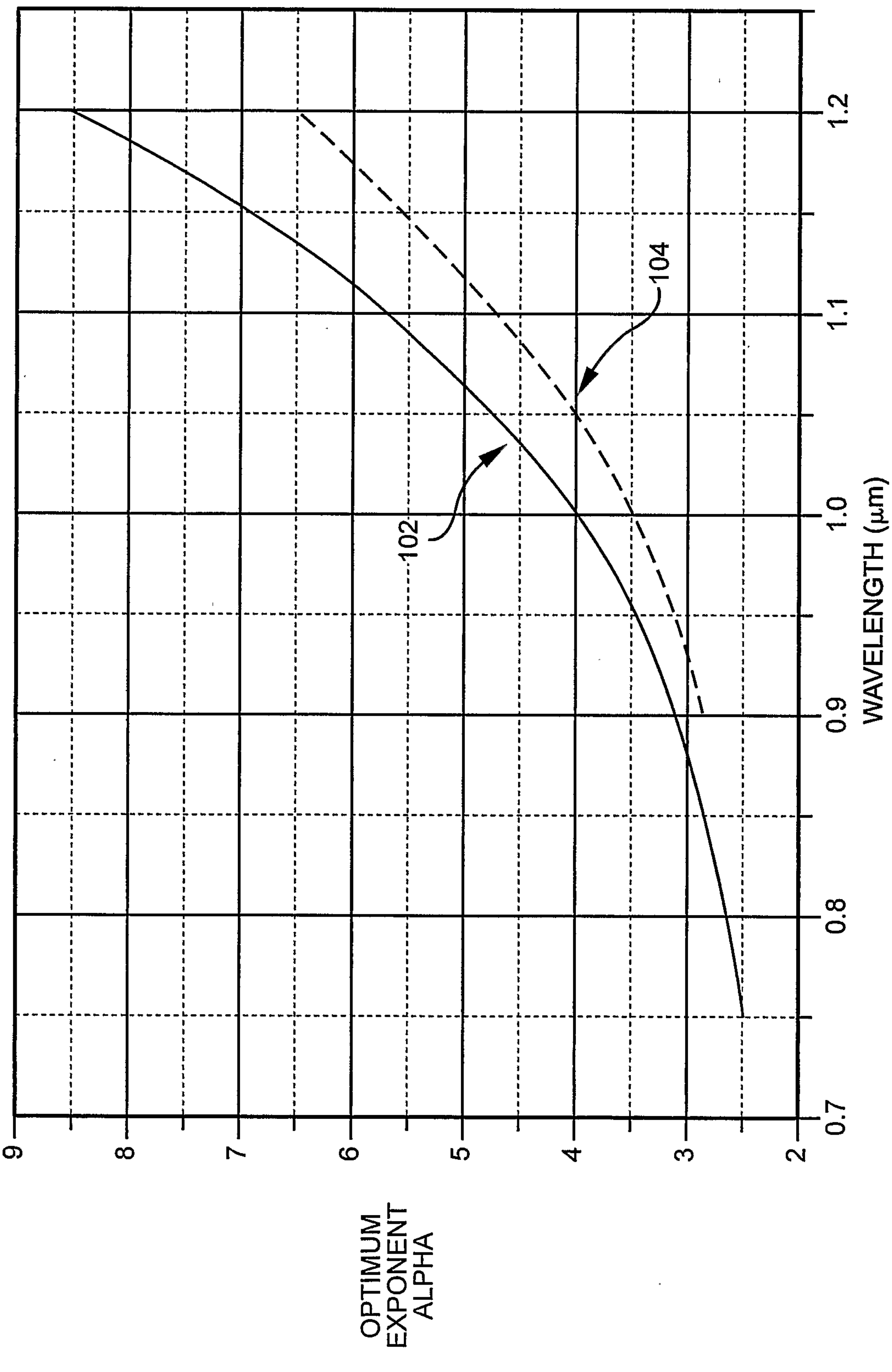

OPTIMUM
EXPONENT
ALPHA
WAVELENGTH (μm)
102
104
9
8
7
6
5
4
3
2
0.7
0.8
0.9
1.0
1.1
1.2

FIG. 13

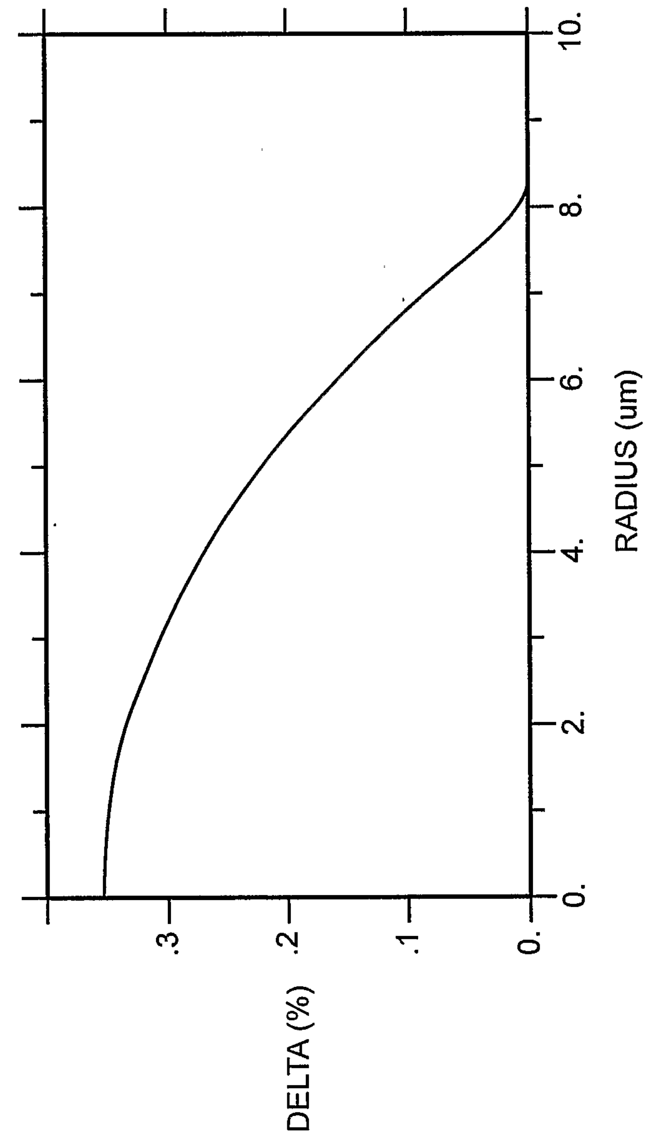


FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US03/05669

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02B 06/02
US CL : 385/123

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 385/123, 124, 125, 126, 127, 128, 141, 142, 143, 144, 145

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Continuation Sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X, P --- A, P	US 2002/0102082 A1 (SARCHI et al) 01 August 2002 (01.08.2002), see Figures 10a and 10b, Tables 13 and 14, and paragraphs [0160]-[0166].	1-4, 10, 11, 18, 21, 23, 24 and 32 ----------- 5-9, 12-17, 19, 20, 22 and 33-36
A	US 2002/0003938 A1 (SRIKANT) 10 January 2002 (10.01.2002), see entire document.	1-24 and 32-36.
A	US 2002/0006259 A1 (TIRLONI) 17 January 2002 (17.01.2002), see entire document.	1-24 and 32-36

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
04 June 2003 (04.06.2003)	30 JUN 2003
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450 Alexandria, Virginia 22313-1450 Facsimile No. (703)305-3230	Authorized officer Michelle R. Connelly-Cushwa Telephone No. 703-308-0956

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US03/05669

Box I Observations where certain claims were found unsearchable (Continuation of Item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claim Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claim Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claim Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of Item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
Please See Continuation Sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: 1-24 and 32-36

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claim(s) 1-24 and 32-36, drawn to an optical fiber having an alpha profile with an alpha parameter in the range of approximately 2 to 8.

Group II, claim(s) 32-36, drawn to a method of designing an optical fiber comprising the step of determining for a given length of fiber a minimum difference between the operating wavelength and the peak bandwidth wavelength.

The inventions listed as Groups I and II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the invention of Group I, as defined in claim 1, is the alpha profile with an alpha parameter in the range of 2 to 8, and the special technical feature of the invention of Group II, as defined in claim 25, is the step of determining for a given length of optical fiber a minimum difference between the operating wavelength and a peak bandwidth wavelength.

Continuation of B. FIELDS SEARCHED Item 3:

USPTO EAST

search terms: optical fiber, fiber optic, refractive index, percent difference, alpha profile, alpha, bandwidth, peak wavelength, central wavelength, separation, offset