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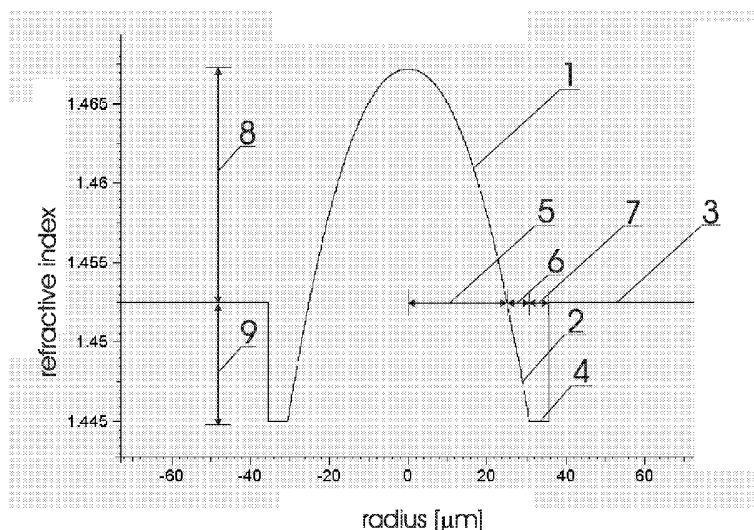
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(54) Title: MULTIMODE OPTICAL FIBER WITH LOW DIFFERENTIAL MODE DELAY



(57) Abstract: The optical multimode fiber according to the invention comprises, in addition to a graded index core, an extended gradient core which has a negative refractive index difference with respect to the cladding. The invention improves the bandwidth, reliability and complexity of the telecommunication systems that are based on multimode fibers. The invention reduces the differential mode delay among modes. The invention thereby allows achieving large bandwidth even in the case when the highest order modes are excited. This has positive effects to the conditions that need to be fulfilled by the components such as optical sources, connectors, fiber couplers, other optical components, cables, etc. The invention eliminates negative impact of the cladding that allows for reduction of fiber core size and the difference between the cladding and the core and thereby allows for achieving the larger bandwidth of optical fiber at lower fiber production cost.

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Multimode optical fiber with low differential mode delay

This invention relates to multimode optical fiber.

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The goal of telecommunication industry is in general the highest possible amount of data transfer in shortest possible time. With the ever increasing number of users and complexity of services there exists a daily increase in demand for the amount of data that can be transferred.

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In the art there are variety of solutions that can be applied to achieve high data rate transfer over longer distances. Optical communications, that were topic of intense research and development in past 20 years, make it possible to achieve a bandwidth not comparable to other technologies. The solutions that are used today in communications over shorter distances are mainly based on multimode fibers. The advantage of multimode fiber lies mainly in the ability to couple this fiber with simple and more cost effective sources. In the past these sources were mainly LEDs with the wavelength around 850nm. Lately, low cost laser diodes with a vertical resonator (VCSEL) have appeared in the market that enable effective coupling between optical fibers and they also achieve high modulation rates.

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Conventional multimode fiber has been known for over 25 years and is standardized by international standards such as ITU-T G.651. According to the most recent recommendations such as OM3, multimode fibers can achieve bandwidths of up to 1.5 GHz.km when all modes of the fiber are excited. But even when the bandwidth of 1.5 GHz.km is achieved, differential mode delay proved to be still over 1 ns/km, which limits further increase of bandwidth. The development of low cost vertical cavity lasers (VCSEL) has lately resulted in a new concept where laser selectively excites only the lower order modes of optical fiber. This results in lower delay between fastest and the slowest excited modes, that allows for achieving the bandwidths in the excess of 1.5 Gbit.km. This approach has been the topic of intense research that lately resulted in the adoption of IEEE 802.3z and IEEE

802.3ae standards. However, the selective excitation of modes in graded index fiber also brings a range of drawbacks. Optical connectors of insufficient quality, bad splices, certain optical components cabling and process of applying the cables can induce mode coupling between the modes that can result in sudden and unexpected degradation of fiber bandwidth. The systems that base on selective excitation also require more complex field test equipment. In addition the selective excitation of modes requires better and narrower range of tolerances for the components that reduces the cost efficiency of the transmission systems. The potential main drawback of selective excitation of the modes in the future can be the lack of compatibility of such concept with the emerging technology of VCSEL arrays. The VCSEL array is composed of larger number of laser diodes with different wavelengths that are integrated on the same chip. Such configuration can allow for efficient wavelength division multiplexing. VCSEL array can be efficiently coupled to an optical fiber under the condition that the fiber core area in which the light needs to be coupled is sufficiently large. Larger VCSEL array therefore cannot be coupled with the multimode fiber while exciting only a limited number of modes.

There is an obvious need to have a multimode fiber with large bandwidth even when an arbitrary or entire set of modes is excited.

There exists a variety of systems that enable the increase of bandwidth of multimode fibers. As already described, most of those systems are based on selective excitation of modes in multimode fibers. There are also individual non-standard solutions that are based on selective excitation of the modes as described for example in patents US 6,580,543 and US 6,330,382. There are solutions that enable archiving the bandwidths over 1.5 GHz.km in an restricted launch but at the same time enable bandwidths over 500 MHz.km while exciting the entire set of modes. Such solutions are presented in US 6,434,309, US 6438,303, US 6,618,543 and US 6,724,965. Dispersion compensation according to US 6,363,195 has also been proposed but its efficiency is limited.

Significant efforts have been also made to develop fiber index profiles that yield high bandwidth to equalize the delay times of high order modes in a multi-mode fiber and to compensate for the center dip. Those efforts were mainly done in the early era of optical fibers. For example in Geshiro et al., "Truncated Parabolic-Index Fiber with Minimum Mode Dispersion," IEEE TRANS. MICROWAVE THEORY AND TECHNIQUES, Vol. MTT-26, No. 2 (February 1978), at p. 115, a parabolic index profile is combined with a cladding jump, which leads to higher bandwidths than with a parabolic profile with no cladding jump. US 6,292,612, discloses MM fiber having a refractive index profile that differs from a conventional α -type profile by at least one of the following: i) a step formed in the index profile at the core/cladding boundary, in conjunction with a linear correction; (ii) a ripple near the core/cladding boundary, in combination with a linear correction, with or without an index step; and iii) an annular ridge formed in the index profile with a center dip. In Stolz and Yevick "Correcting Multimode Fiber Profiles with Differential Mode Delay", J. Optical Communications, vol 4 (1983), no 4 pp. 139-147 trimming of the MMF core edge to reduce the highest order modes differential delay has been proposed.

The idea of reducing the higher order mode delay by extension of graded index core beneath the cladding level was first proposed in K. Okamoto and T. Okoshi, "Analysis of Wave Propagation in Optical Fibers Having Core with a α -Power Refractive-Index Distribution and Uniform Cladding" IEEE Transactions on Microwave Theory and Techniques, 24(7), pp.416-421, March 1976. In this work the α -profile multimode fiber profile was extended below the cladding level (e.g., outside the core/cladding boundary region), with a negative cladding jump. The supporting analysis demonstrated that the absolute value of negative extension of the α -core beneath the cladding level needs to be approximately of the same depth as the absolute difference between the maximum refractive index of the core at its center and the cladding level. In case of common silica telecommunication multimode fiber with index $\Delta=1\%$, such negative refractive index core extension beneath the cladding would need to be approximately -1% . This is a condition that is not technically and economically compatible with current manufacturing techniques for silica-based fibers. However, in

plastic optical fiber where negative index differences of the profile with the respect to the cladding are easy to achieve, this approach has been already successfully applied, see T. Ishigure, H., K. Ohdoko, and Y. Koike, "High-Bandwidth Plastic Optical Fiber With W-Refractive Index Profile", IEEE Photonics Technology Letters, 16 (9), pp. 2081-2083, September 2004. Further efforts were conducted to develop this concept in Katsunari Okamoto and Takanori Okoshi in "Computer-Aided Synthesis of the Optimum Refractive-Index Profile for a Multimode Fiber" IEEE Transactions on Microwave Theory and Techniques, 25(3), pp. 213-221, March 1977. A trial and error algorithm was used to automatically search for an optimum fiber profile shape that includes the extension of the core beneath the cladding level. The result of numerical optimisation was an optimal profile, which is reported to be a smoothed W-shaped profile (e.g., FIG. 1 thereof). This synthesized profile was similar to α -profile fiber in the region with positive relative refractive index difference, however in the region near the edges of the core where the index difference was below the cladding level, the smoothed shape deviating from α -alpha profile was characteristic. The maximum absolute value of the relative index difference of the core extension and the cladding level was still in the best case one half of the absolute difference between the maximum refractive index of the core at its center and the cladding level. In case of standard 50 μm fiber the index maximum relative negative index difference of the profile would need to be below -0.5% while the region would require precise shaping in accordance with the results of numerical optimization process. While such profiles may be advantageous in leading to high bandwidths, they are barely incompatible with the manufacturing process for silica-based fiber. It is known from the literature that achieving negative index difference in silica fiber manufacturing process close or below -0.5% is very difficult and uneconomical, especially if precise control of the profile is required. In addition, it is believed that such profiles may lead to leaky modes as the regions with the negative index difference are deep and wide and provide good isolation of leaky modes from the cladding.

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This invention relates to multimode optical fiber that can achieve a bandwidth in excess of 5 GHz.km while exciting an arbitrary set of

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modes. Such fiber is intended for high speed data communications over shorter distances, but other applications are also possible.

5 The technical problem solved by the invention is the reduction of differential mode delay that limits the bandwidth of the telecommunication system. The invention presents profile designs of multimode optical fibers, which can achieve a bandwidth of over 5 GHz.km regardless of the excited set of modes, including the cases when in a multimode fiber the highest order modes are excited
10 or the entire set of modes is excited.

In the present invention the problem is solved by introduction of special structure in the profile of multimode optical fiber that enables the equalization of the group velocities of higher and lower order modes
15 and is at the same time compatible with current manufacturing processes.

The present invention uses core extension beneath the cladding level to minimize the differential mode delay among the modes. However,
20 the negative index differences are appropriately small to enable practical and economical fiber manufacturing. This is achieved by introduction of depression with negative index of refraction relative to the cladding around the extended core. In addition, the entire core of the fiber resembles α or nearly α -profile including the section that
25 extends beneath the cladding level that further simplifies fiber manufacturing and differentiates this invention from current state of the art.

30 The invention will be described using examples and figures.

Fig.1 shows the logarithm of relative time delay (RTD) in standard 50 μm optical fiber at the wavelength of 850 nm. Each dot in the figure presents one linearly polarized mode. Many dots are overlapping.
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Fig.2 shows the logarithm of relative time delay (RTD) in standard 50 μm optical fiber at the wavelength of 1310 nm. Each dot in the figure presents one linearly polarized mode. Many dots are overlapping.

- 5 Fig.3 shows an example of an improved profile with the definition of depressed extended core and depression.

10 Fig.4 shows logarithm of relative time delay (RTD) in improved 50 μm optical fiber at the wavelength of 850 nm. Each dot in the figure presents one linearly polarized mode. Many dots are overlapping.

15 Fig.5 shows the logarithm of relative time delay (RTD) in improved 50 μm optical fiber at the wavelength of 1310 nm. Each dot in the figure presents one linearly polarized mode. Many dots are overlapping.

Fig 6 shows absolute delay in improved 50 μm optical fiber at 850 nm for different profile parameters. Each dot in the figure presents one linearly polarized mode. Many dots are overlapping.

20 Fig. 7 shows absolute delay in improved 50 μm optical fiber at 1310 nm for different profile parameters. Each dot in the figure presents one linearly polarized mode. Many dots are overlapping.

25 Fig 8 shows absolute delay in reduced core optical fibers at 850 nm for different profile parameters. Each dot in the figure presents one linearly polarized mode. Many dots are overlapping.

30 Fig 9 shows absolute delay in reduced core optical fibers at 1310 nm for different profile parameters. Each dot in figure presents one linearly polarized mode. Many dots are overlapping.

35 Detailed numerical analysis has shown that it is not possible to achieve a bandwidth significantly over 1.5 GHz.km when the entire set of modes is excited in a standard multimode fiber. It is generally known that the modal dispersion is minimized by application of the α -profile of the optical fiber that is defined as

$$n(r) = n_{\max}(1 - 2\Delta(r/a)^\alpha)^{1/2} \text{ for } r < a$$

and

$$n_{\max}(1 - 2\Delta)^{1/2} \text{ for } r \geq a$$

5 where r is a coordinate in the radial direction of a cylindrical optical fiber, a is core radius, $n(r)$ is refractive index of the optical fiber at radius r , n_{\min} is the minimum refractive index (in standard fiber this is the refractive index of the cladding), n_{\max} is the maximum refractive index of the fiber core, α is a parameter of the profile, and Δ is defined
10 as

$$\Delta = (n_{\max}^2 - n_{\min}^2) / (2n_{\max}^2).$$

15 The profile of standard multimode fibers is composed of a graded index core that is defined by upper equation that describes α -profile of the optical fiber and cladding with the constant refractive index n_{\min} . The α -parameter of the profile is around the value of 2, depending on the wavelength for which the fiber is optimized.

20 The detailed numerical analysis showed that the conventional α -profile does not allow for minimization of highest order mode group delays when compared to the lower order modes, as shown in Figs 1 and 2. Figs 1 and 2 represent the logarithm of relative time delay (RTD) as a function of difference between the effective indices of the modes and
25 cladding level. The RTD is defined as:

$$RTD = \frac{|\text{group delay of the fundamental mode} - \text{group delay of the observed higher order mode}|}{\text{group delay of the observed higher order mode}}$$

30 Figs. 1 and 2 show that the delays of the highest order modes are significantly larger when compared to delays of the lower order modes, which results in pronounced modal dispersion and thereby limits the bandwidth of the optical fiber when higher order modes are excited. Large delays are the consequence of negative impact of the cladding with the constant refractive index of refraction on the propagation of the
35 higher order modes. In fact, a significant portion of the evanescent field of the highest order modes propagates in the cladding where effect of

the group velocity equalization, provided by the graded index core is not present.

5 The presented invention solves the problem of negative impact of the cladding in accordance with Fig. 3 in a way to introduce into the known multimode fiber profile that is composed of core 1 with radius a 5 and reflection index difference Δ_1 8 and cladding 3, additional profile structures:

10 a) depressed extended core 2 with radial dimension b 6 and relative refractive index difference Δ_2 9 with respect to the cladding 3 that is a continuation of the primary core 1 with α -profile.

15 b) depression 4 with radial dimension c 7 and relative refractive index difference Δ_2 9 with the respect to the cladding 3, which encircles the extended core.

The introduced profile structures have two effects: the major fractions of the evanescent highest order modal fields propagate in the extended
20 depressed core 2, that has α -profile shape and thereby enables good equalization of group velocities of highest order modes, and assures better confinement of the highest order modal fields to the main core 1 and extended core 2. The final effect is such that the fraction of the evanescent field of the highest order modes that propagate in the
25 cladding with the constant index of refraction 3 becomes negligible. This enables very good equalization of group velocities of higher order modes as shown in Figs 4 and 5. Both figures clearly show significant reduction (improvement) of relative delay between modes when compared to Figs 1 and 2. The set of parameters for depressed
30 extended core 2 and index depression 4, that allows for equalization of group velocities is broad and wavelength depended. For the practical manufacturability of the fibers, the minimal dimensions of both profile features are important. Larger extended core 2 requires smaller dimensions of the depression 4 and vice versa. In an extreme case the
35 depression 4 can be omitted, but in such a case the size and depth of the extended core 2 increases to the level impractical for fiber manufacturability.

Figs. 6 and 7 present absolute delays between individual modal groups for the case of fiber with following parameters: $2a=50\ \mu\text{m}$, $\Delta_1=1\%$, $\Delta_2=-0.5\%$, $b=5.5$, $c=5\ \mu\text{m}$ and $\alpha=2.087$ at 850 nm and $\alpha=2.0$ at 1310 nm. Figs. 6 and 7 clearly show that the largest modal delays between the modes do not exceed 0.057 ns/km at 850 nm and 0.053 ns/km at 1310 nm. Achieving the bandwidths in excess of 10 GHz.km is therefore possible even when all modes of the fiber are excited.

A systematic numerical investigation was carried out to determine practical and minimal radial dimensions of b (in Fig. 3 marked by 6) of the extended core, radial dimensions c (in Fig. 3 marked by 9) that enable effective elimination of the cladding influence and thereby minimization of modal dispersion. Table 1 demonstrates practically determined fiber profile parameters that limit the modal dispersion caused by cladding influence below the theoretical value that is achievable with an ideal α -profile fiber with the core size of $2a=50\ \mu\text{m}$ and $\Delta_1=1\%$.

Table 1:

	850 nm	1310 nm
$\Delta_2=-0.3\ \%$	$b=4.4\ \mu\text{m}, c=3\ \mu\text{m}$	-
$\Delta_2=-0.35\ \%$	$b=4.9\ \mu\text{m}, c=1\ \mu\text{m}$	$b=4\ \mu\text{m}, c=5\ \mu\text{m}$
$\Delta_2=-0.5\ \%$	$b=5.35\ \mu\text{m}, c=0\ \mu\text{m}$	$b=5.5\ \mu\text{m}, c=1\ \mu\text{m}$

The successful control over the cladding influences enables further reduction of fiber core size a and Δ_1 below the values that are typical for standard fibers. In case where only the core size a and Δ_1 would be reduced, without eliminating the cladding influence, the fiber would not have significantly better bandwidth than is currently available by standard fibers. The introduction of extended depressed core 2 and depression 4 therefore allows for reduction of the radius a of the core 1 and the refractive index difference Δ_1 that is reflected in an bandwidth increase and lowering of fiber production cost. The reduction of Δ_1 namely reduces the contents of germanium, that is the most expensive material in multimode fiber production. In order to maintain sufficient

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resistance of such fiber to bend losses, the reduced core fiber needs to have appropriate profile parameters that enable sufficient separation of the modal groups in the phase constant space. The differences between effective indexes of refraction for neighboring modal groups shall be as large as in standard multimode fibers. In practice this means that the difference between effective indexes between modal groups shall be around 0.001 at the wavelength of 1310 nm and 0.0007 at the wavelength of 850 nm. The practical examples of profile parameters for such fibers with the radius of $a=19 \mu\text{m}$ and $a=15 \mu\text{m}$ are shown in table 2.

Table 2:

Core	850 nm				1310 nm			
	α	Δ_2 [%]	b [μm]	c [μm]	α	Δ_2 [%]	b [μm]	c [μm]
$a=15 \mu\text{m},$ $\Delta_1=0.36 \%$	2.1027	-0.25	4.24	3	2.015	-0.4	6.7	5
$a=19 \mu\text{m},$ $\Delta_1=0.578 \%$	2.0965	-0.35	4.81	3	2.01	-0.45	6.27	5

In spite of the reduced core size, the presented fibers can be effectively coupled to existing VCSEL.

The core radius reduction a and Δ_1 is reflected in significant increase of bandwidth as shown in Figs. 8 and 9. The maximum delay between the slowest and the fastest mode is for the 19 μm fiber less than 18 ps/km and less than 5 ps/km for the fiber with $a=15 \mu\text{m}$. This makes it possible to achieve a theoretical bandwidth of 50 to 100 GHz.km.

To an expert in art of optical fibers it is clear that the values of parameters presented in the tables 1 and 2 present only typical examples and variations of these parameters can be found that will provide similar or equal performances that where shown in presented practical examples.

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Claims:

1. A multimode optical fiber comprising:
 - 5 - a graded index core (1) having a radius a (5) greater than $23\ \mu\text{m}$ and smaller than $33\ \mu\text{m}$, a relative refractive index difference Δ_1 (8) between the core center and a cladding (3) being greater than 0.9%,
 - a depressed extended gradient core (2) which is an extension of said graded index core (1), the depressed extended gradient core (2) having the radial dimension b (6) which is greater than $3\ \mu\text{m}$ and
10 smaller than $5.5\ \mu\text{m}$, a relative refractive index difference Δ_2 (9) between the minimum of the extended gradient core (2) and the cladding (3) having a negative value between -0.45% and -0.1%,
 - a depression (4) surrounding said extended gradient core (2), the refractive index of said depression being negative with respect to the
15 cladding (3) and the radial dimension c (7) of the depression (4) being between $1\ \mu\text{m}$ and $5\ \mu\text{m}$, and
 - the cladding (3) surrounding said depression (4).
- 20 2. The multimode optical fiber according to claim 1, wherein said graded index core (1) and/or said extended gradient core (2) has an α -profile.
3. The multimode optical fiber according to claim 2, wherein said
25 extended gradient core (2) has an α -profile which is a continuation of the α -profile of the graded index core (1).
4. The multimode optical fiber according to any of the foregoing claims
30 1 to 3, wherein the maximum differential group delay between the fastest and the slowest guided mode is smaller than $0.5\ \text{ns/km}$,
5. The multimode optical fiber according to any of the foregoing claims
35 1 to 3, wherein the difference between the effective indices of the neighbouring modal groups is at least 0.001 at the wavelength of $1310\ \text{nm}$ and at least 0.0007 at the wavelength of $850\ \text{nm}$.
6. A multimode optical fiber comprising:

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- a graded index core (1) having a radius a (5) greater than $15\ \mu\text{m}$ and smaller than $23\ \mu\text{m}$, a relative refractive index difference Δ_1 (8) between the core center and a cladding (3) having a value between 0.3% and 0.9%,
 - 5 - a depressed extended gradient core (2) which is an extension of said graded index core (1), the depressed extended gradient core (2) having the radial dimension b (6) which is greater than $3\ \mu\text{m}$ and smaller than $7\ \mu\text{m}$, a relative refractive index difference Δ_2 (9) between the minimum of the extended gradient core (2) and the cladding (3)
 - 10 having a negative value between -0.5% and -0,15%,
 - a depression (4) surrounding said extended gradient core (2), the refractive index of said depression being negative with respect to the cladding (3) and the radial dimension c (7) of the depression (4) being between $1\ \mu\text{m}$ and $5\ \mu\text{m}$, and
 - 15 - the cladding (3) surrounding said depression (4).
7. The multimode optical fiber according to claim 6, wherein said graded index core (1) has an α -profile.
- 20 8. The multimode optical fiber according to claim 7, wherein said extended gradient core (2) has an α -profile which is a continuation of the α -profile of the graded index core (1).
- 25 9. The multimode optical fiber according to any of the foregoing claims 6 to 8, wherein the difference between the effective indices of the neighbouring modal groups is at least 0.001 at the wavelength of $1310\ \text{nm}$ and at least 0.0007 at the wavelength of $850\ \text{nm}$.
- 30 10. An optical telecommunications system comprising an optical transmitter, an optical receiver and an optical multimode optical fiber, said optical multimode optical fiber comprising:
- a graded index core (1) having a radius a (5) greater than $22\ \mu\text{m}$ and smaller than $27\ \mu\text{m}$, a relative refractive index difference Δ_1 (8) between the core center and a cladding (3) having a value between
 - 35 0.7% and 1.5%,
 - a depressed extended gradient core (2) which is an extension of said graded index core (1), the depressed extended gradient core (2)

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having the radial dimension b (6) which is greater than $3\ \mu\text{m}$ and smaller than $6\ \mu\text{m}$, a relative refractive index difference Δ_2 (9) between the minimum of the extended gradient core (2) and the cladding (3) having a negative value between -0.4% and -0.2% ,

- 5 - a depression (4) surrounding said extended gradient core (2), the refractive index of said depression being negative with respect to the cladding (3) and the radial dimension c (7) of the depression (4) being between $1\ \mu\text{m}$ and $7\ \mu\text{m}$, and
- the cladding (3) surrounding said depression (4).

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11. The optical telecommunications system according to claim 10, wherein said graded index core (1) has an α -profile.

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12. The multimode optical fiber according to claim 11, wherein said extended gradient core (2) has an α -profile which is a continuation of the α -profile of the graded index core (1).

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13. The optical telecommunications system according to any of the foregoing claims 10 to 12, wherein the bandwidth of the system is greater than $5\ \text{GHz.km}$, and a complete set or an arbitrary set of guided modes is adapted to be excited in said optical multimode optical fiber

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14. The optical telecommunications system according to claim 13, wherein the bandwidth of the system is greater than $10\ \text{GHz.km}$.

15. The optical telecommunications system according to claim 13, wherein the bandwidth of the system is greater than $20\ \text{GHz.km}$.

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16. The optical telecommunications system according to any of the foregoing claims 10 to 14, wherein the transmitter is a VCSEL.

17. An optical telecommunications system comprising an optical transmitter, an optical receiver and an optical multimode optical fiber, said optical multimode optical fiber comprising:

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- a graded index core (1) having a radius a (5) greater than $17\ \mu\text{m}$ and smaller than $23\ \mu\text{m}$, a relative refractive index difference Δ_1 (8)

- between the core center and a cladding (3) having a value between 0.5% and 0.75%,
- a depressed extended gradient core (2) which is an extension of said graded index core (1), the depressed extended gradient core (2) having the radial dimension b (6) which is greater than $3\ \mu\text{m}$ and smaller than $6\ \mu\text{m}$, a relative refractive index difference Δ_2 (9) between the minimum of the extended gradient core (2) and the cladding (3) having a negative value between -0.45% and -0,2%,
 - a depression (4) surrounding said extended gradient core (2), the refractive index of said depression being negative with respect to the cladding (3) and the radial dimension c (7) of the depression (4) being between $1\ \mu\text{m}$ and $7\ \mu\text{m}$, and
 - the cladding (3) surrounding said depression (4).
- 15 18. The optical telecommunications system according to claim 17, wherein said graded index core (1) has an α -profile.
19. The multimode optical fiber according to claim 18, wherein said extended gradient core (2) has an α -profile which is a continuation of the α -profile of the graded index core (1).
- 20 20. An optical telecommunications system comprising an optical transmitter, an optical receiver and an optical multimode optical fiber, said optical multimode optical fiber comprising:
- 25 - a graded index core (1) having a radius a (5) greater than $14\ \mu\text{m}$ and smaller than $17\ \mu\text{m}$, a relative refractive index difference Δ_1 (8) between the core center and a cladding (3) having a value between 0.5% and 0.7%,
 - a depressed extended gradient core (2) which is an extension of said graded index core (1), the depressed extended gradient core (2) having the radial dimension b (6) which is greater than $3\ \mu\text{m}$ and smaller than $6\ \mu\text{m}$, a relative refractive index difference Δ_2 (9) between the minimum of the extended gradient core (2) and the cladding (3) having a negative value between -0.45% and -0,2%,
 - 30 - a depression (4) surrounding said extended gradient core (2), the refractive index of said depression being negative with respect to the
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cladding (3) and the radial dimension c (7) of the depression (4) being between $1\ \mu\text{m}$ and $7\ \mu\text{m}$, and
- the cladding (3) surrounding said depression (4).

5 21. The optical telecommunications system according to claim 20, wherein said graded index core (1) has an α -profile.

10 22. The multimode optical fiber according to claim 21, wherein said extended gradient core (2) has an α -profile which is a continuation of the α -profile of the graded index core (1).

15 23. An optical telecommunication system comprising an optical transmitter, a receiver and a multimode optical fiber, said multimode fiber having a refractive index profile with graded index core (1) with radius a (5), that is larger than $22\ \mu\text{m}$ and less than $27\ \mu\text{m}$ and refractive index difference Δ_1 (8), that is larger than 0.7% and less than 1.5%, depressed extended gradient core (2) with radial dimension b (6) and negative refractive index difference Δ_2 (9), that is between -0.1% and -0.5% , depression (3) refractive index difference Δ_2 (9) and the
20 cladding (4) extending to the outer edge of the fiber.

24. The optical telecommunication system according to claim 23, wherein the bandwidth of the system is greater than 5 Gbit.km and the complete set of guided modes is excited in said multimode fiber.

25 25. An optical telecommunication system comprising an optical transmitter, a receiver and a multimode optical fiber, said multimode fiber having a refractive index profile with graded index core (1) with radius a (5), that is larger than $22\ \mu\text{m}$ and less than $27\ \mu\text{m}$ and refractive index difference Δ_1 (8), that is larger than 0.7% and less than 1.5%, depressed extended gradient core (2) with radial dimension b (6) and negative refractive index difference Δ_2 (9), that is between -0.1% and -0.5% , depression (3) with refractive index difference Δ_2 (9) and the cladding (4) extending to the outer edge of the fiber.
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26. The optical telecommunication system according to claim 25, wherein the bandwidth of the system is greater than 10 Gbit.km and the complete set of guided modes is excited in said multimode fiber.

5 27. A multimode optical fiber, that supports propagation of more than 7 linearly polarized modes and poses the maximum differential mode delay among guided modes that is less than 0.5 ns/km, said fiber comprising a graded index core (1) with radius a (5), that is larger than 22 μm and less than 27 μm and refractive index difference Δ_1 (8), that is larger than 0.7% and less than 1.5%, depressed extended gradient core (2) with radial dimension b (6) and negative refractive index difference Δ_2 (9), that is between -0.1% and -0.5%, depression (3) with refractive index difference Δ_2 (9) and the cladding (4) extending to the outer edge of the fiber.

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28. The multimode optical fiber according to claim 27, wherein the difference between effective indexes of the neighboring modal groups is at least 0.001 at wavelength of 1310nm and at least 0.0007 at wavelength of 850nm.

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29. A multimode optical fiber, that supports propagation of more than 5 linearly polarized modes and poses the maximum differential mode delay among guided modes that is less than 0.25 ns/km, said fiber comprising of a graded index core (1) with radius a (5), that is larger than 22 μm and less than 27 μm and refractive index difference Δ_1 (8), that is larger than 0.7% and less than 1.5%, depressed extended gradient core (2) with radial dimension b (6) and negative refractive index difference Δ_2 (9), that is between -0.1% and -0.5%, depression (3) with refractive index difference Δ_2 (9) and the cladding (4) extending to the outer edge of the fiber.

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30. The multimode optical fiber according to claim 29, wherein the difference between effective indexes of the neighboring modal groups is at least 0.001 at wavelength of 1310nm and at least 0.0007 at wavelength of 850nm.

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- 5 31. A multimode optical fiber comprising a graded index core (1) with an α profile shape with radius a (5), extended depressed gradient core (2) with the α profile shape that is continuation of gradient index core (1) with the radial dimension of depressed extended core that is more than $0.4 \mu\text{m}$ and less than $15 \mu\text{m}$, the relative difference of refractive indexes Δ_2 (9) between the outer edge of extended depressed core and the cladding (3) is between -0.1% and -0.4% , the depression (4) that surrounds extended gradient core (2) and has radial dimension larger than $15 \mu\text{m}$.
- 10
- 15 32. A multimode optical fiber comprising a graded index core (1) with an α profile shape and radius a (5), that is larger than $15 \mu\text{m}$ and less than $26 \mu\text{m}$, relative refractive index difference Δ_1 (8) between the core center and the cladding (3), that is between 0.3% and 1% , depressed extended gradient core (2) with an a profile shape which is continuation of graded index core (1), with radial dimension b is more than $1 \mu\text{m}$ and less than $7 \mu\text{m}$, depression (3) that surrounds extended gradient core and has radial dimension between $2 \mu\text{m}$ and $35 \mu\text{m}$, the relative index difference Δ_2 (9) between the outer depression (4) and the cladding (3) is between -0.1% and -0.5% , and the cladding (3) that surrounds the depression (4).
- 20
- 25 33. An optical telecommunication system comprising an optical transmitter, a receiver and a multimode optical fiber, said multimode fiber having a refractive index profile with graded index core (1) with radius a (5), that is larger than $5 \mu\text{m}$ and less than $55 \mu\text{m}$ and refractive index difference Δ_1 (8), that is larger than 0.35% and less than 2.1% , depressed extended gradient core (2) with radial dimension b and negative refractive index difference Δ_2 (9), depression (4) with radial dimension c (7) and refractive index difference Δ_2 (9) and the cladding extending to the outer edge of the fiber.
- 30
- 35 34. The optical telecommunication system according to claim 33, wherein the bandwidth of the system is greater than 1.5 Gbit.km and the complete set of guided modes is excited in said multimode fiber.

35. The multimode optical fiber according to claim 34, wherein the radial dimension b (6) of the depressed extended gradient core (2) is more than $1\ \mu\text{m}$ and less than $10\ \mu\text{m}$.
- 5 36. The multimode optical fiber according to claim 34, wherein the absolute value of refractive index difference Δ_2 is more than 0.15% and less than 1.5%.
- 10 37. The multimode optical fiber with according to claim 34, wherein the radial dimension of depression c (7) is between 0 and $35\ \mu\text{m}$.
- 15 38. The multimode optical fiber according to claim 34, wherein the difference between effective indexes of the neighboring modal groups is at least 0.001 at wavelength of 1310nm and at least 0.0007 at wavelength of 850nm.
- 20 39. The multimode optical fiber according to claim 34, comprising a depressed extended core (2) with radial dimension (6) between $0.5\ \mu\text{m}$ and $5\ \mu\text{m}$ and negative difference of refractive index Δ_2 with an absolute value between 0.15% and 0.7% and depression with radial dimension c (7) between 0 and $7\ \mu\text{m}$.
- 25 40. A multimode optical fiber, that supports propagation of more than 7 linearly polarized modes comprising of a graded index core (1), depressed extended core (2) with negative index difference Δ_2 (9) and radial dimension b (6), that is larger than $2\ \mu\text{m}$, depression (3) with the radial dimension c (7) and cladding (4) up to the outer edge of the fiber.
- 30 41. The multimode optical fiber according to claim 40, comprising a gradient core (1) with the radius a (5), that is more than $7\ \mu\text{m}$ and less than $70\ \mu\text{m}$ and the refractive index difference Δ_1 (8), with absolute value that is more than 0.35% and less than 2.1%.
- 35 42. The multimode optical fiber according to claim 40, wherein the radial dimension b (6) of depression extended core (2) is between 0 and $7\ \mu\text{m}$.

43. The multimode optical fiber according to claim 40, wherein the absolute value of refractive index difference Δ_2 is more than 0.2% and less than 2%.
- 5 44. The multimode optical fiber according to claim 40, wherein the radial dimension of depression c (7) is between 0 and 35 μ m.
45. The multimode optical fiber according to claim 40, wherein the difference between effective indexes of the neighboring modal groups is at least 0.001 at wavelength of 1310nm and at least 0.0007 at
10 wavelength of 850nm.
46. The multimode optical fiber with profile according to claim 40, comprising a depressed extended core (2) with radial dimension b (6)
15 between 0 μ m and 5 μ m, absolute value of refractive index difference Δ_2 (9) that is between 0.17 % and 0.5% and depression (3) with radial dimension c (7) between 0 μ m and 10 μ m.
47. An optical telecommunication system comprising an optical
20 transmitter, a receiver and a multimode optical fiber, said multimode fiber having a refractive index profile with graded index core (1) with radius a (5), that is larger than 5 μ m and less than 55 μ m and refractive index difference Δ_1 (8), that is larger than 0.35% and less than 2.1%, depressed extended gradient core (2) with radial dimension
25 b between 2 μ m and 10 μ m and the cladding (4) extending to the outer edge of the fiber.
48. An optical telecommunication system comprising an optical
30 transmitter, a receiver and a multimode optical fiber, said multimode fiber having a refractive index profile with graded index core (1) with radius a (5), that is larger than 5 μ m and less than 55 μ m and refractive index difference Δ_1 (8), that is larger than 0.35% and less than 2.1%, depressed extended gradient core (2) with radial dimension
35 b between 1 μ m and 10 μ m and the cladding (4) extending to the outer edge of the fiber.

49. The optical telecommunication system according to claim 48, wherein said optical fiber comprises a cladding (4) that extends to the outer edge of the fiber and is composed of two or more layers of material with different refractive indexes with radial dimensions between 0 and 100 μm and refractive index difference with the respects to outer most layer that has an absolute value between 0 and 2%.

50. An optical telecommunications system comprising an optical transmitter, a receiver and a multimode optical fiber, the bandwidth of the system being greater than 1.5 Gb.km, an arbitrary set of guided modes being adapted to be excited in said multimode fiber, said multimode fiber having a refractive index profile with graded index core (1) with radius a (5), that is larger than 5 μm and less than 55 μm and refractive index difference Δ_1 (8), that is larger than 0.35% and less than 2.1%, depressed extended gradient core (2) with radial dimension b and negative refractive index difference Δ_2 (9), depression (3) with radial dimension c (7) and refractive index difference Δ_2 (9) and the cladding extending to the outer edge of the fiber.

51. The optical telecommunications system according to claim 50, wherein the where radial dimension b (6) of the depressed extended gradient core (2) is more than 1 μm and less than 10 μm .

52. The optical telecommunications system according to claim 51, wherein the absolute value of refractive index difference Δ_2 is more than 0.15% and less than 1.5%.

53. The optical telecommunications system according to claim 51, wherein the radial dimension of depression c (7) is between 0 and 35 μm .

54. The optical telecommunications system according to claim 51, wherein the difference between effective indexes for the neighboring modal groups is at least 0.001 at wavelength of 1310nm and at least 0.0007 at wavelength of 850nm.

55. The multimode optical fiber according to claim 34, comprising a depressed extended core (2) with radial dimension (6) between 0.5 μm and 5 μm and negative difference of refractive index Δ_2 with an absolute value between 0.15% and 0.7% and depression with radial dimension c (7) between 0 and 10 μm .

56. A multimode optical fiber comprising a graded index core (1) with radius a (5), that is larger than 10 μm and less than 35 μm , depressed extended gradient core (2), with the α profile shape and is continuation of gradient index core (1) while the radial dimension of depressed extended core is more than 0.5 μm and less than 7 μm , depression (4), that surrounds extended gradient core and has radial dimension between 0 and 20 μm and cladding (3) that surrounds the depression (4) and has radial dimension that is larger than 15 μm .

57. A multimode optical fiber comprising a graded index core (1) with an α profile shape with radius a (5), that is larger than 10 μm and less than 35 μm , depressed extended gradient core (2), with an α profile shape and is continuation of gradient index core (1) while the radial dimension of depressed extended core is more than 0.5 μm and less than 7 μm , multilayer or graded cladding (3) that surrounds gradient core and has radial dimension larger than 15 μm .

58. A multimode optical fiber comprising a graded index core (1) with an α profile shape with radius a (5), that is larger than 7 μm and less than 35 μm , and with the relative difference of refractive indexes Δ_1 (8) between the core center and the cladding that is between 0.3% and 2%, extended depressed gradient core (2) with the α profile shape and is continuation of gradient index core (1) while the radial dimension of depressed extended core is more than 0.2 μm and less than 15 μm , the relative difference of refractive indexes Δ_2 (9) between the outer edge of extended depressed core and the cladding is between -0.1% and -0.7% , depression (4), that surrounds extended gradient core and has radial dimension between 0 and 35 μm with the negative refractive index difference Δ_2 (9) between depression (4) and cladding (3) is between -0.1% and -0.7% and the cladding (3) (3) that surrounds the depression (4) and has radial dimension that is larger than 15 μm .

59. A multimode optical fiber comprising a graded index core (1) with an α profile shape with radius a (5), that is larger than $7\ \mu\text{m}$ and less than $35\ \mu\text{m}$, and with the relative difference of refractive indexes Δ_1 (8) between the core center and the cladding that is between 0.3% and 2%, extended depressed gradient core (2) with the α profile shape that is continuation of gradient index core (1) while the radial dimension of depressed extended core is more than $0.2\ \mu\text{m}$ and less than $15\ \mu\text{m}$ with the relative difference of refractive indexes Δ_2 (9) between the outer edge of extended depressed core and the cladding between -0.1% and -0.7% , depression (4), and the cladding (3) that surrounds the extended depression gradient core (2) and has radial dimension that is larger than $15\ \mu\text{m}$.
60. A multimode optical fiber comprising a graded index core (1) with an α profile shape, extended depressed gradient core (2) with the α profile shape that is continuation of gradient index core (1) while the radial dimension of depressed extended core is more than $0.2\ \mu\text{m}$ and less than $15\ \mu\text{m}$ with the relative difference of refractive indexes Δ_2 (9) between the outer edge of extended depressed core and the cladding is between -0.1% and -0.7% , depression (4), and the cladding (3) that surrounds the extended depression gradient core (2) and has radial dimension that is larger than $15\ \mu\text{m}$.
61. A multimode optical fiber comprising of a graded index core (1) with an α profile shape, extended depressed gradient core (2) with the α profile shape and is continuation of gradient index core (1) while the radial dimension of depressed extended core is more than $0.4\ \mu\text{m}$ and less than $15\ \mu\text{m}$ with the relative negative difference of refractive indexes Δ_2 (9) between the outer edge of extended depressed core and the cladding is between -0.15% and -0.7% , depression (4), and the cladding (3) that surrounds the extended depression gradient core (2) and has radial dimension that is larger than $15\ \mu\text{m}$.
62. A multimode optical fiber comprising a graded index core (1) with an α profile shape with radius a (5), that is larger than $7\ \mu\text{m}$ and less than $20\ \mu\text{m}$ with the relative difference of refractive indexes Δ_1 (8)

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between the core center and the cladding of 0.3% and 1%, extended depressed gradient core (2) with the α profile shape that is continuation of gradient index core (1) while the radial dimension of depressed extended core is more than 1 μm and less than 7 μm , depression (4) that surrounds the extended depressed gradient core (2) and has radial dimension between 0 and 35 μm , and the relative negative difference of refractive indexes Δ_2 (9) between the depression (4) and the cladding (3) that is less than -0.1% and the cladding (3) that surrounds the depression (4).

10

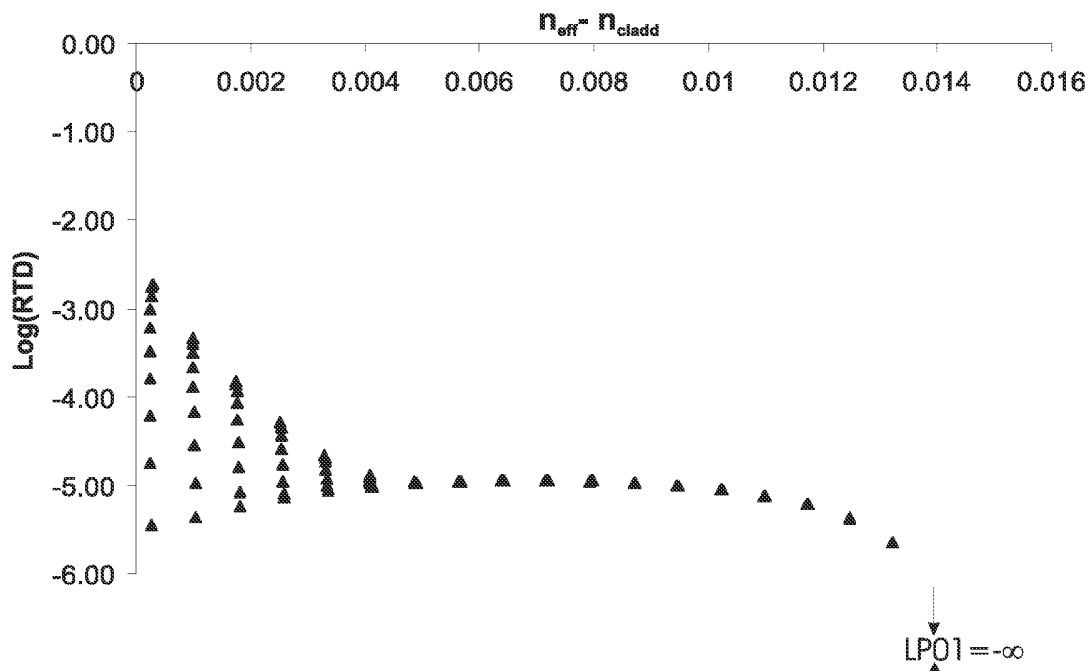


Fig. 1

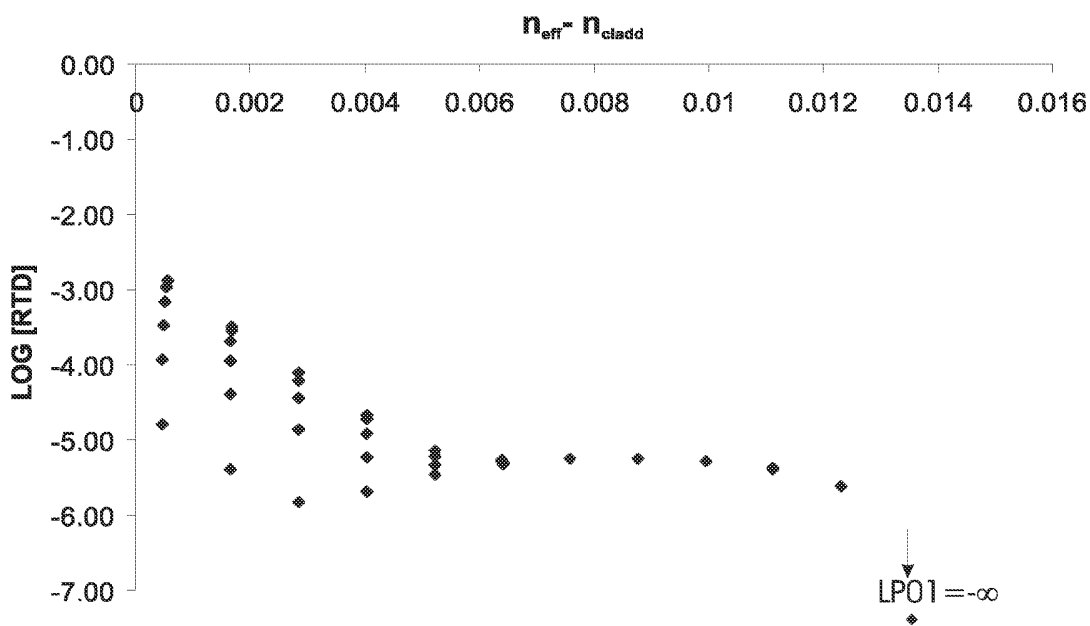


Fig. 2

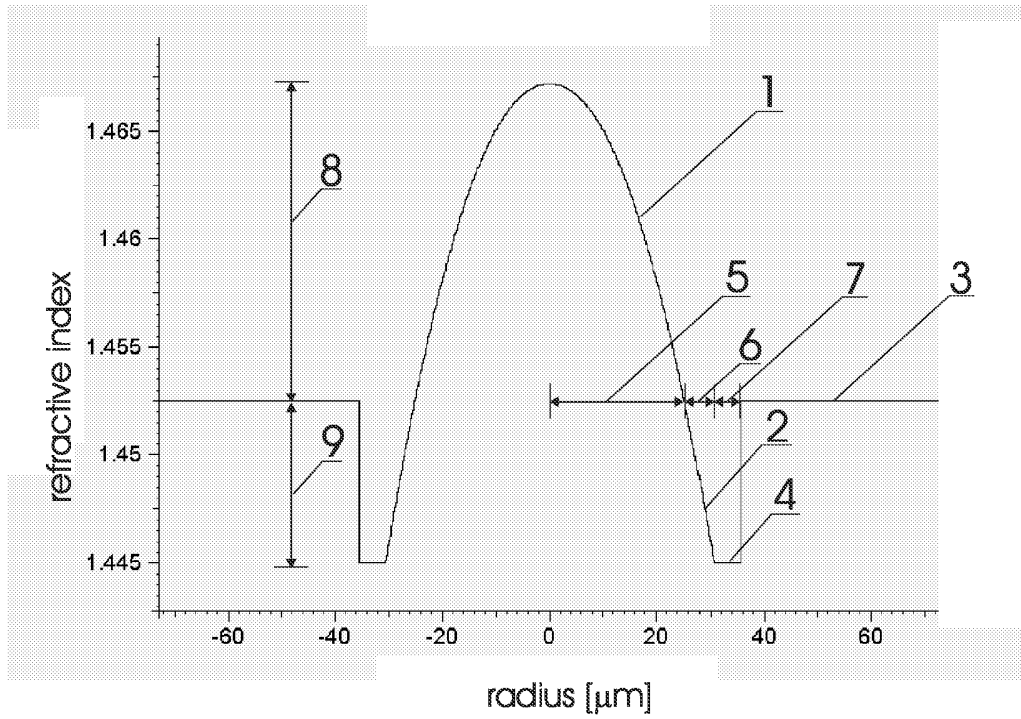


Fig. 3

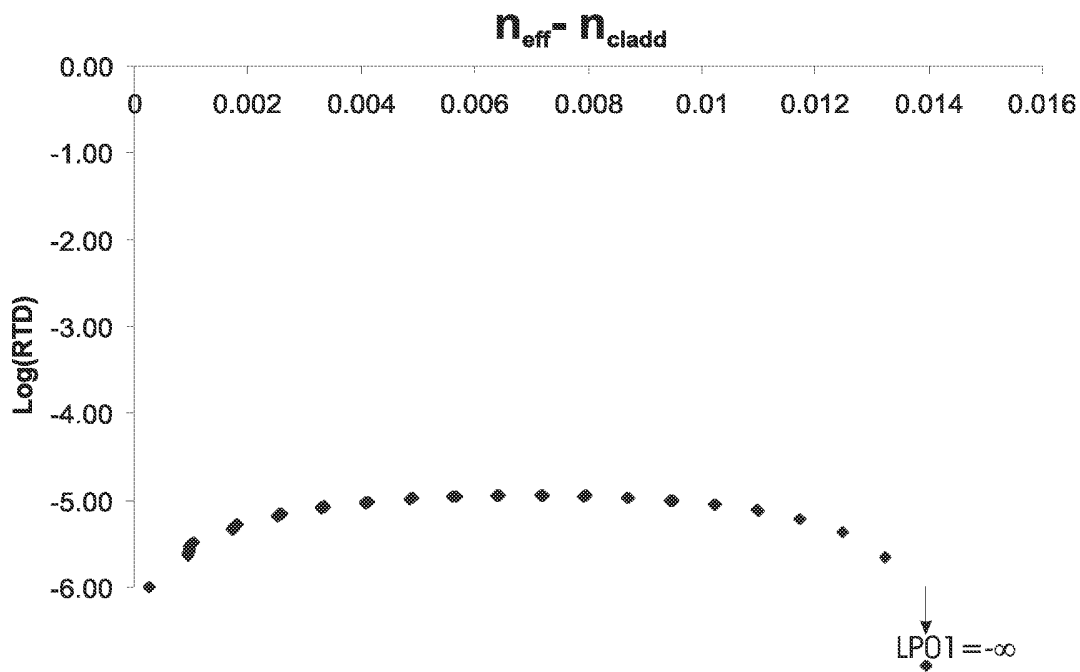


Fig. 4

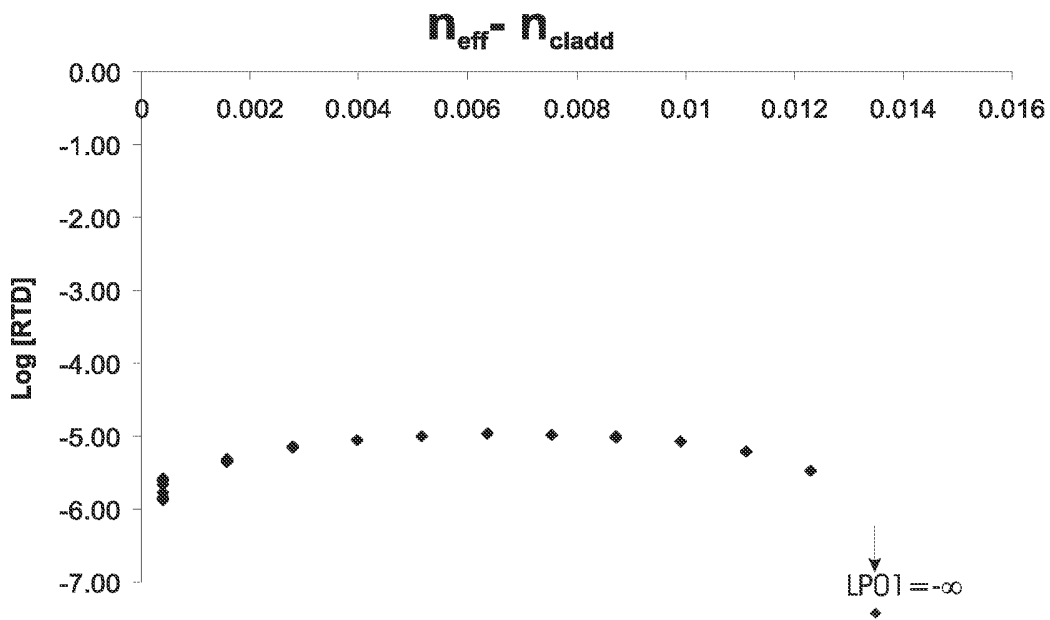


Fig. 5

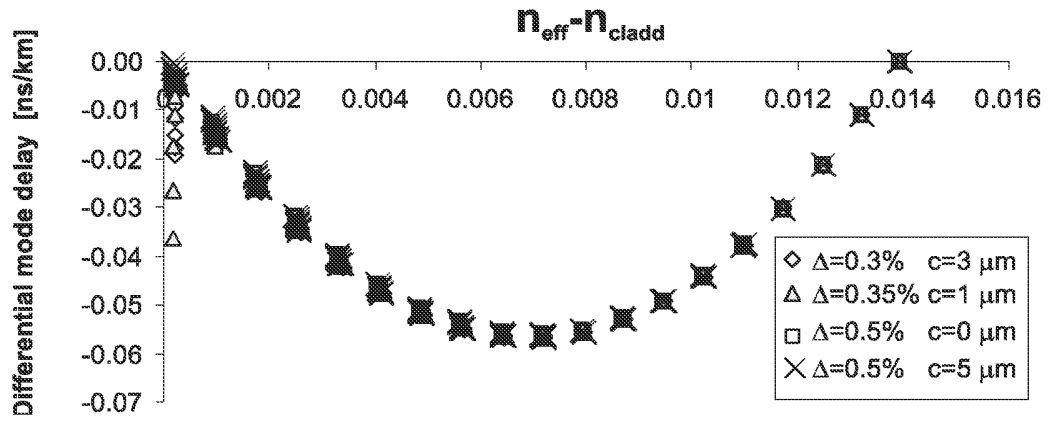


Fig. 6

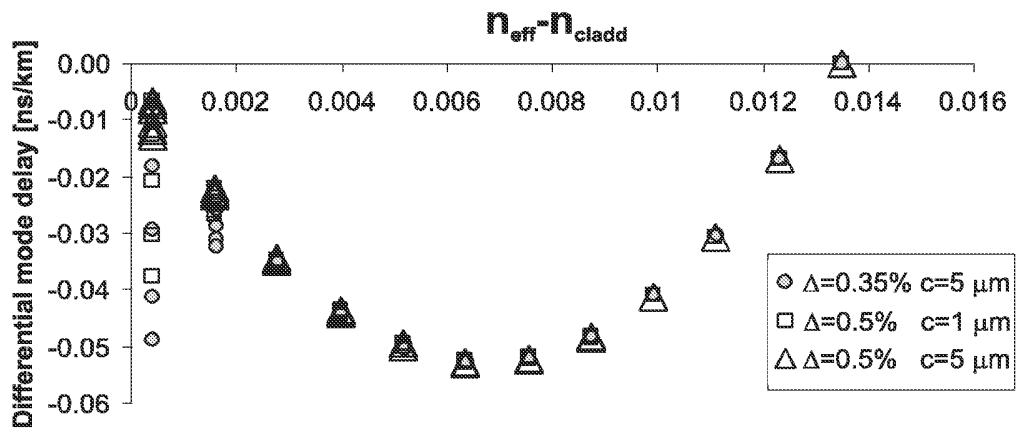


Fig. 7

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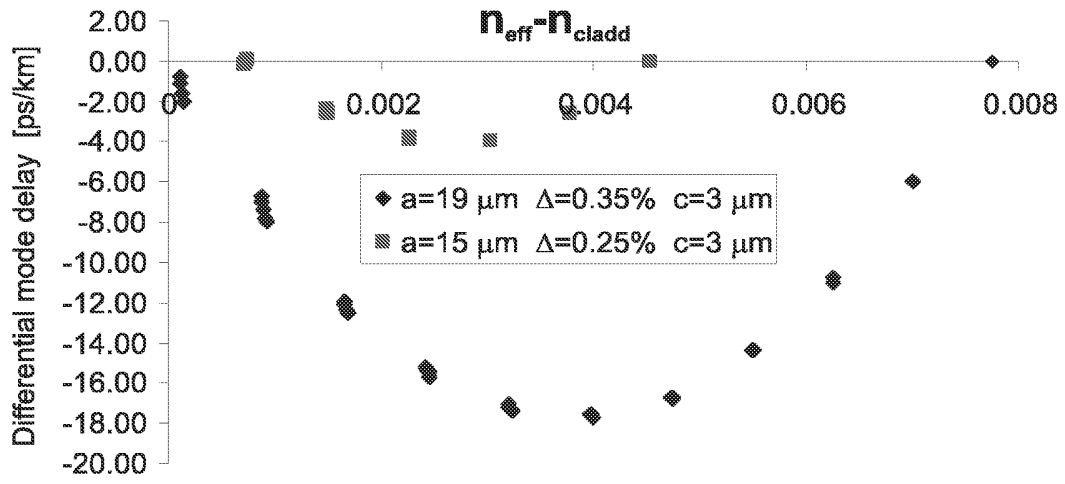


Fig. 8

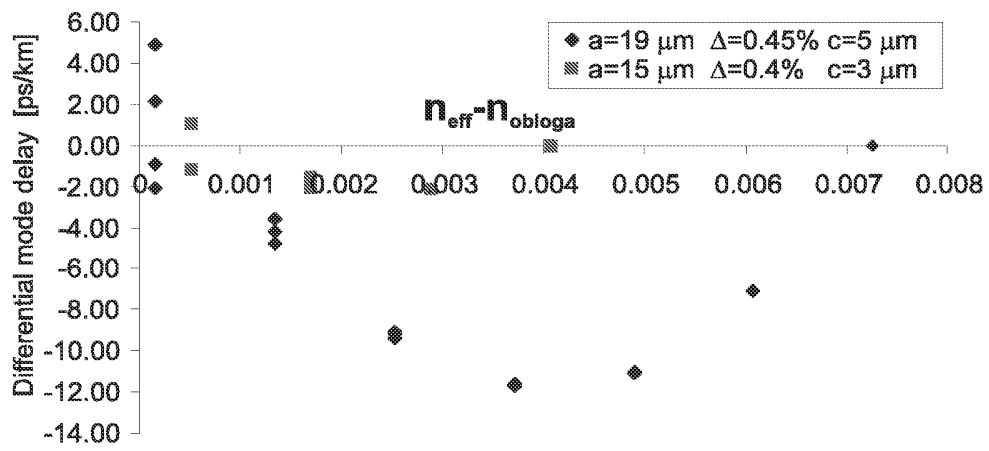


Fig. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/FI2005/050284

A. CLASSIFICATION OF SUBJECT MATTER See extra sheet 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) IPC7 G02B Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched FI, SE, NO, DK; G02B Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-internal, WPI, PAJ		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1043609 A1 (FURUKAWA ELECTRIC CO LTD) 11 October 2000 (11.10.2000), Fig. 1, Table 1	33, 35-37, 40, 42-44, 46-48, 50-53, 60, 61
X	EP 1083446 A1 (FURUKAWA ELECTRIC CO LTD) 14 March 2001 (14.03.2001), Fig 2, Table 1	33, 35-37, 39, 40, 42-44, 46-48, 50-53, 58-61
X	EP 1116970 A1 (FURUKAWA ELECTRIC CO LTD) 18 July 2001 (18.07.2001), Fig. 3, Table 3	33, 35-37, 40, 42-44, 46, 48, 50-53, 60, 61
X,P	EP 1477831 A1 (FITEL USA CORP A DELAWARE CORP) 17 November 2004 (17.11.2004), Fig. 5	60, 61
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> 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 but 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 31 October 2005 (31.10.2005)		Date of mailing of the international search report 07 November 2005 (07.11.2005)
Name and mailing address of the ISA/FI Patentti- ja rekisterihallitus PL 1160, 00101 Helsinki Facsimile No. +358 9 6939 5328		Authorized officer Olli-Pekka Sievänen Telephone No. +358 9 6939 500

INTERNATIONAL SEARCH REPORT

International application No.

PCT/FI2005/050284

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

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

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

2. Claims Nos.: 4-5, 9, 13-15, 24, 26-30, 34, 38, 40-46, and 50-55
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:
In claims 4-5, 9, 13-15, 24, 26-30, 34, 38, 40-46, and 50-54, an invention has been defined by desirable characteristics or properties, such as "maximum differential group/mode delay", "difference between effective indices", "the bandwidth of the system", and "a number of supported linearly polarized modes." These properties refer to results to be achieved, not to the structural technical features of the fibre. Due to the omission of these technical features, a meaningful search is not possible. Claims 40-44,46,50-53 have been searched in part. Claims 4,5,9,13-15,24,26-30,34,38,45,54 have not been searched. Claim 55 has not been searched, because it is not clear to which claim this dependent claim is referring.

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

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

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 additional fees, this Authority did not invite payment of additional fees.

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.:

Remark on Protest

- The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/FI2005/050284

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CLASSIFICATION OF SUBJECT MATTER

G02B 6/036 (2006.01)i

G02B 6/028 (2006.01)i