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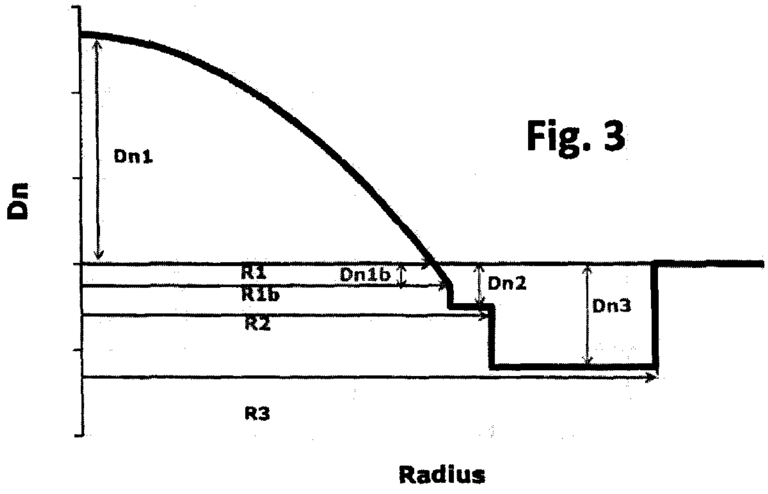

Fig. 3

(57) **Abstract**: A Few Mode Fiber supporting 25 or 30 LP guided modes comprises: A graded index core with a α-profile, a radius R_1 (at 0 refractive index difference) between 21.5 and 27μm and a maximum refractive index difference Dn_1 between $12.5x10^{-3}$ and $20x10^{-3}$, and an end of the α-profile at a radius R_{1b}, with index difference Dn_{1b}; A trench surrounding the core with radius R_3 between 30 and 42μm and refractive index difference Dn3 between -15.10_{-3} and -6.10^{-3}, An intermediate depressed trench with a radius R_2, with $R_{1b}<R_2<R_3$ and a refractive index difference Dn_2, with $Dn_3<Dn_2<0$, wherein : for I $Dn_{1b}-Dn_2$ | >=0.5x10-3, Min(Dn_{1b}, Dn_2) < -1.5x10-3, and for I $Dn_{1b}-Dn_2$ | <0.5x10-3, Dn_2 is between -5x10-3 and -3.5x10-3.

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Few mode optical fibers for mode division multiplexing.

1. FIELD OF THE INVENTION

The present disclosure relates to the field of fiber optic transmission, and, more specifically, to improved few-mode fiber designs for mode division multiplexing.

2. BACKGROUND

An optical fiber is conventionally constituted of an optical core, which transmits an optical signal, and of an optical cladding, which confines the optical signal within the optical core. To that end the refractive index of the core, n_0, is greater than the one of the cladding, n_{Cl}. An optical fiber is generally characterized by a refractive index profile that associates the refractive index (n) with the radius (r) of the optical fiber: the distance r with respect to the center of the optical fiber is shown on x-axis and the difference Dn between the refractive index at radius r, n(r), and the refractive index of the optical cladding n_{Cl} is shown on y-axis.

Nowadays, two main categories of optical fibers exist: multimode fibers and single-mode fibers. In a multimode fiber, for a given wavelength, several optical modes can propagate simultaneously along the optical fiber, whereas in a single-mode fiber, the higher order modes (hereafter called HOMs) are cut-off or highly attenuated.

Single-mode fibers are commonly used for long-distance applications, such as access networks, metropolitan networks or long-haul networks. To obtain an optical fiber capable to transmit a single-mode optical signal, a core with a relatively small diameter is required (typically between 5 µm and 15 µm). To meet requirements of high speed or bit-rate applications (for example 10Gbps), standard single-mode fibers require use of a modulated single-mode laser emitter tuned to work typically at a wavelength of 1550 nm. However, single-mode fibers suffer from nonlinearity problems, which are major limitations on fiber transmission capacity.

Multimode fibers are commonly used for short-distance applications requiring a high bandwidth, such as local area networks (LANs), multi-dwelling units (MDUs), and data centers, more generally known as in-building networks. The core of a multimode fiber typically has a diameter of 50 µm, or 62.5 µm. The most prevalent multimode fibers in telecommunications are the refractive graded-index profile optical fibers. By minimizing the intermodal dispersion (i.e. the difference between the propagation delay times or group velocity of the optical modes along the optical fiber, also called DMGD for Differential Mode Group Delay), such a refractive index profile guaranties a high modal bandwidth for a given wavelength.

Since data traffic over fiber optic networks continues to grow exponentially, there is an increasing demand for increasing per-fiber traffic particularly across long distances. To this end, multiplexing techniques have been developed that allow a plurality of separate data streams to share the same optical fiber. Among these techniques, one promising approach is space division multiplexing (SDM), in which a plurality of data channels within a single optical fiber are provided by a respective plurality of optical signal modes guided by the fiber.

Such a technique has required the development of new types of optical fibers, called few-mode optical fibers, which support more than one spatial mode but fewer spatial modes than the multi-mode fibers. Such few-mode fibers, which are notably discussed in the PCT patent document WO2011/094400, support 2 LP modes or more.

Space-division-multiplexed transmissions using Few-Mode Fibers (FMFs) have hence recently received considerable attention because of their potential to multiply the capacity of single-mode transmissions by the number of modes that will be used.

One approach to the design of Few-Mode Fibers consists of minimizing the Differential Mode Group Delays (DMGDs, i.e. the difference in the respective arrival times of the guided modes used for spatial multiplexing), so that all modes can be simultaneously detected using complex 2Nx2N (N being the total number of spatial modes, i.e. including LP (Linear Polarization) mode degeneracies) multiple-input-multiple-output (MIMO) techniques, regardless mode-coupling phenomena that is one of the limiting factor to bridge long distances. In this approach, a careful design of the FMF is required in order to reduce the DMGD (preferably below 300 ps/km to preserve MIMO efficiency) while still providing low bend losses for all guided LP modes.

This optimization, however, becomes more and more difficult when the number of LP modes increases. So far, only FMFs supporting up to 20 usable LP modes with low Differential Modes Group Delays (DMGDs) have been reported.

In ***"50μm Multimode Fibers for Mode Division Multiplexing"*** **(proc. Ecoc 4.2.1 – 2015)**, P. Sillard et al. disclose 50μm-diameter graded-index core multimode fibers, which can be adapted to mode-division-multiplexed transmissions that use MIMO digital signal processing and selective mode multiplexing. Such fibers were realized and characterized and compared to low-differential-mode-group-delay few-mode fibers.

Figure 1 illustrates the refractive index difference with respect to the radius of such a FMF with a core diameter of 50μm that supports 30 LP modes at 1550 nm but in which only 20 LP modes are usable. Actually, a severe degradation of the bend losses prevents the use of the 9th and 10th mode groups in space-division-multiplexed systems for such fibers.

Patent document **US 2015/0168643** discloses a few-mode fiber, having a graded-index core and a surrounding cladding comprising a layer between the core and the trench, a down-doped trench abutting the layer, and an undoped cladding region abutting the trench. The fiber's refractive index profile is configured to support 9 to 20 LP modes for transmission of a spatiallymultiplexed optical signal. Undesired modes have respective effective indices that are close to, or less than, the cladding index so as to result in leakage of the undesired modes into the outer cladding. The index spacing between the desired mode having the lowest effective index and the leaky mode with the highest effective index is sufficiently large so as to substantially prevent coupling there between.

Although such designs are promising, they do not allow supporting 25 or 30 usable LP modes while reducing the Differential Mode Group Delays as much as desired. In addition, the profiles disclosed in both documents are not optimized to ensure low bend losses, which, however, are mandatory for FMFs.

Accordingly, a need exists for designs for Few-Mode optical Fibers guiding an increased number of supported modes (25 LP modes or more), with small differential mode group delays between any combination of LP guided modes (preferably below 200 ps/km) and low bend losses (preferably below 100 dB/turn at 10 mm bend radius).

3. SUMMARY OF THE INVENTION

In one particular embodiment of the present disclosure, an optical fiber is proposed comprising a central optical core surrounded by an optical cladding. The optical core has a α graded-index profile $n(r)$ with α between 1 and 3, α being a non-dimensional parameter that defines an index profile shape of said optical core, that is a function of a radial distance r from the center of said optical core. The optical core has a maximum refractive index n_0 and an outer radius R_{1b} with a refractive index difference $Dn_{1b} = n(R_{1b}) - n_{Cl}$ with respect to said optical cladding having at its outer edge a refractive index n_{Cl}. The optical core also has a radius R_1, such that $n(R_1) = n_{Cl}$, comprised between 21.5 µm and 27 µm and a maximum refractive index difference $Dn_1 = n_0 - n_{Cl}$ between $12.5\text{x}10^{-3}$ and 20×10^{-3}, said refractive index difference being determined at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended.

Moreover, the optical cladding comprises:

- a region of depressed refractive index n_{trench}, called a trench, surrounding the optical core, said trench having an outer radius R_3 between 30 µm and 42 µm, and a refractive index difference $Dn_3 = n_{trench} - n_{Cl}$ between the trench and the cladding comprised between $-15\text{x}10^{-3}$ and $-6\text{x}10^{-3}$;
- an intermediate region of depressed refractive index, called an intermediate trench, surrounding the optical core, said intermediate trench having an outer radius R_2, with

$R_{1b} < R_2 < R_3$, and a refractive index difference Dn_2 between the intermediate trench and the cladding, with $Dn_3 < Dn_2 < 0$.

Said optical fiber is such that:

- for $|Dn_{1b} - Dn_2| \geq 0.5\times10^{-3}$, $Min(Dn_{1b}, Dn_2) \leq -1.5\times10^{-3}$, and
- for $|Dn_{1b} - Dn_2| < 0.5\times10^{-3}$, Dn_2 is between -5×10^{-3} and -3.5×10^{-3}.

As used herein, and unless otherwise specified, the term "α graded-index profile" refers to an optical core having a refractive index profile n(r) defined as follows:

$$n(r) = n_0\sqrt{1 - 2\Delta\left(\frac{r}{R_{1b}}\right)^{\alpha}}, r \leq R_{1b}$$

where:

r is a variable representative of the radius of the optical fiber,

R_{1b} is the optical core outer radius,

Δ is the normalized refractive index difference, with $\Delta = \frac{n_0^2 - n_1^2}{2n_0^2}$

n_1 is the minimal refractive index of the optical core,

n_0 is the maximal refractive index of the optical core,

α is a non-dimensional parameter that defines the index profile shape of the optical core.

An alpha parameter $\alpha = 2$ corresponds to an inverted parabola. An alpha parameter $\alpha = 1$ corresponds to a triangular shape, while an alpha parameter $\alpha = \infty$ corresponds to a step function.

Such a FMF optical fiber shows a larger core diameter, as compared to prior art FMF fibers, which allows supporting an increased number of LP modes. Moreover, it comprises a depressed trench, which leads to decrease the macrobending losses by improving the confinement of the optical modes within the core. Such a design thus allows to significantly improve the trade-off between DMGD and bend losses.

Last, such a FMF optical fiber presents a carefully designed interface between the graded-index core and the trench, which allows keeping the DMGDs between any combination of LP guided modes low while keeping the bend loss of any LP guided modes low as well.

According to an embodiment, such an optical fiber has a normalized frequency $V = \frac{2\pi R_1}{\lambda_c}\sqrt{n_0^2 - n_{Cl}^2}$ between 18.4 and 23.

According to an embodiment, such an optical fiber guides at least 25 LP modes.

According to another embodiment, such an optical fiber guides at least 30 LP modes.

Such a high number of guided modes allows increasing the capacity of an optical system comprising such a few-mode optical fiber, and answers the demand for higher bandwidth in long-haul optical transmission systems.

A few-mode fiber according to an embodiment of the present disclosure thus guides an increased number of LP modes that can efficiently be used in space-division multiplexed transmissions, as compared to prior art FMFs.

According to a further embodiment, $Max|DMGDs| < 200ps/km$ at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended, where $DMGD$ is the Differential Mode Group Delay between two guided modes in said optical fiber, and where Max|DMGDs| is the absolute maximum value of DMGD between any combination of guided modes. DMGD can be characterized, for instance, by using the standard differential-mode-delay measurement procedure of multimode fibers, i.e. measuring pulses responses of the fiber for single-mode launches that radially scan the fiber core (a centered launch excites the lowest-order modes, while large offset launches excite the highest-order modes).

According to yet a further embodiment, $Max|DMGDs| < 500ps/km$ for $\lambda\epsilon[\lambda_C - \delta\lambda;\ \lambda_C + \delta\lambda]$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended and where $2\delta\lambda$ is a width of said operating band.

The Differential Mode Group Delays are hence very low, while the challenge of increasing the number of LP modes up to 25 or 30 is met.

According to an embodiment, the fundamental LP_{01} mode guided by said optical fiber has an effective area A_{eff}>150µm² at $\lambda = \lambda_C$. Such a relatively large effective area limits intra-mode non-linearity.

According to a further embodiment, $Max|BL| < 100dB/turn$, preferably <50dB/turn, at 10mm bend radius at $\lambda = \lambda_C$, where BL are the bend losses of the different guided modes in said optical fiber, and where $Max|BL|$ is the absolute maximum value of BL for all guided modes. BL can be characterized, for instance, by measuring the loss difference of a given mode selected by a mode multiplexer and injected in the few-mode fiber with and without applying a loop of 10mm radius using a spectral attenuation bench.

Such a few-mode fiber thus shows a very good trade-off between bend losses and Differential Mode Group Delays.

According to an embodiment, λ_c=1550 nm and $\delta\lambda$= 20 nm.

It is noted that the FMFs described herein and throughout the document are suitable for use within, at a minimum, the entire "C-band" (1530nm - 1565nm), but also in some cases the S- (1460nm – 1530nm), L- (1565nm - 1625nm) and U-bands (1625nm – 1675nm). The Differential Mode Group Delays of such FMFs are hence very low on all the extended C-band.

Another aspect of the disclosure concerns an optical link comprising at least one optical fiber as described here above in any of its embodiments.

Such an optical link may comprise any number of concatenated optical fibers, as long as one of them at least complies with the features set forth in the present disclosure. Such an optical link may also comprise several optical fibers, which would all comply with the features of the present disclosure.

According to an embodiment, an optical link is provided, which comprises N optical fibers, with $N \geq 2$, N being an integer,

each optical fiber of index $i \in [\![1; N]\!]$ comprising a central optical core and an optical cladding surrounding the optical core, the optical core having a α_i graded-index profile $n_i(r)$ with α_i between 1 and 3, α_i being a non-dimensional parameter that defines an index profile shape of the optical core, that is a function of a radial distance r from the center of said optical core,

and the optical core having a maximal refractive index n_{0i}, and an outer radius R_{1bi} with a refractive index difference $Dn_{1bi} = n_i(R_{1bi}) - n_{Cli}$ with respect to said optical cladding having at its outer edge a refractive index n_{Cli}, said optical core also having a radius R_{1i}, such that $n_i(R_{1i}) = n_{Cli}$, and a maximum refractive index difference $Dn_{1i} = n_{0i} - n_{Cli}$,

said optical cladding comprising:

- a region of depressed refractive index $n_{trenchi}$, called a trench, surrounding the optical core, said trench having an outer radius R_{3i}, and a refractive index difference $Dn_{3i} = n_{trenchi} - n_{Cli}$ between the trench and the cladding;
- an intermediate region of depressed refractive index, called an intermediate trench, surrounding the optical core, said intermediate trench having an outer radius R_{2i}, with $R_{1bi} < R_{2i} < R_{3i}$, and a refractive index difference Dn_{2i} between the intermediate trench and the cladding, with $Dn_{3i} < Dn_{2i} < 0$.

Such an optical link is such that:

- an average optical core radius R_{1link} for said optical link is comprised between 21.5 µm and 27 µm, where $R_{1link} = \frac{\sum_{i=1}^{N} R_{1i}L_i}{\sum_{i=1}^{N} L_i}$ with L_i a length of optical fiber i in said link,
- an average maximum refractive index difference Dn_{1link} for said optical link is between 12.5×10^{-3} and 20×10^{-3}, where $Dn_{1link} = \frac{\sum_{i=1}^{N} Dn_{1i}L_i}{\sum_{i=1}^{N} L_i}$, at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended,
- an average trench outer radius R_{3link} for said optical link is between 30 µm and 42 µm, where $R_{3link} = \frac{\sum_{i=1}^{N} R_{3i}L_i}{\sum_{i=1}^{N} L_i}$ with L_i a length of optical fiber i in said link,

- an average refractive index difference between the trench and the cladding Dn_{3link} for said optical link is comprised between -15x10^{-3} and -6x10^{-3}, at $\lambda = \lambda_C$, where $Dn_{3link} = \frac{\sum_{i=1}^{N} Dn_{3i}L_i}{\sum_{i=1}^{N} L_i}$,

and:

- for $|Dn_{1blink} - Dn_{2link}| \geq 0.5\times10^{-3}$, $Min(Dn_{1blink}, Dn_{2link}) \leq -1.5\times10^{-3}$, and
- for $|Dn_{1blink} - Dn_{2link}| < 0.5\times10^{-3}$, Dn_{2link} is between -5×10^{-3} and -3.5×10^{-3}

where $Dn_{2link} = \frac{\sum_{i=1}^{N} Dn_{2i}L_i}{\sum_{i=1}^{N} L_i}$ is the average refractive index difference between the intermediate trench and the cladding for said optical link and where $Dn_{1blink} = \frac{\sum_{i=1}^{N} Dn_{1bi}L_i}{\sum_{i=1}^{N} L_i}$ is the average refractive index difference between the core at its outer radius and the cladding for said optical link, both at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical link is intended.

By properly choosing the respective lengths L_i of all optical fibers constituting the optical link, it is possible to build a few-mode optical fiber link, which allow guiding an increased number of LP modes as compared to prior art FMFs, while reaching the lowest Differential Mode Group Delay. Such an optical link is hence a DMGD-compensated FMF link and may show improved properties over the individual FMFs comprised in said optical link. Such low DMGD allow all modes being simultaneously detected using 2Nx2N (N being the total number of spatial modes, i.e. including LP mode degeneracies) MIMO ("Multiple Input Multiple Output") techniques, regardless mode coupling phenomena. The system reach is thus increased over prior art.

Such an optical link shows properties similar to those described previously in relation to the FMF optical fiber, notably in terms of number of LP modes supported, and low values of DMGDs. Optical fibers comprised in this optical link show depressed trenches, which allow decreasing the macrobending losses by improving the confinement of the optical modes within the core.

According to an embodiment, such an optical link has a normalized frequency $V_{link} = \frac{2\pi R_{1link}}{\lambda_c}\sqrt{n_{0link}^2 - n_{Cllink}^2}$ comprised between 18.4 and 23, where $n_{0link} = \frac{\sum_{i=1}^{N} n_{0i}L_i}{\sum_{i=1}^{N} L_i}$ is the average maximum refractive index of the core for said optical link, and where $n_{Cllink} = \frac{\sum_{i=1}^{N} n_{Cli}L_i}{\sum_{i=1}^{N} L_i}$ is the average refractive index of the cladding for said optical link.

According to an embodiment, such an optical link guides at least 25 LP modes.

According to an embodiment, such an optical link guides at least 30 LP modes.

According to a further embodiment, for all optical fibers $i \in [\![1; N]\!]$ in said link, said lengths L_i are chosen so as to minimize $Max|DMGD_{link}|$ on said link, where $DMGD_{link}$ is the Differential Mode Group Delay between two guided modes in said optical link, and where

Max|$DMGD_{link}$| is the absolute maximum value of Differential Mode Group Delay between any combination of guided modes in said optical link.

According to yet a further embodiment, at least two optical fibers in said link have $DMGD_i$ showing opposite signs for at least one mode guided by said optical fibers, where $DMGD_i$ is the Differential Mode Group Delay between said one mode and any other guided mode in optical fiber i.

Hence, such an optical link may be formed with optical fibers which meet the criteria set forth above in relation to the optical fiber according to embodiments of the disclosure, but differ from each other within a certain tolerance and show Differential Mode Group Delays with opposite signs, which may compensate each other once assembled in an optical link. A tolerance of $\pm 0.5\times 10^{-3}$ on the refractive index differences, of $\pm 0.5\mu m$ on the radii of the fiber, and of ±0.02 on the α, is acceptable for optical fibers forming such an optical link.

According to an embodiment, $Max|DMGD_{link}| < 200ps/km$ at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended.

According to a further embodiment, $Max|DMGD_{link}| < 500ps/km$ for $\lambda\epsilon[\lambda_C - \delta\lambda;\ \lambda_C + \delta\lambda]$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended and where $2\delta\lambda$ is a width of said operating band.

According to yet another embodiment, $Max|BL_{link}| < 100dB/turn$, preferably <50dB/turn, at 10mm bend radius at $\lambda = \lambda_C$, where BL_{link} are the bend losses of the different guided modes in said optical link, and where $Max|BL_{link}|$ is the absolute maximum value of BL_{link} for all guided modes in said optical link.

Preferably, λ_c=1550 nm and $\delta\lambda$= 20 nm.

The present disclosure also concerns an optical link comprising N optical fibers, with $N \geq 2$, N being an integer. Each optical fiber complies with the requirements set forth above according to embodiments of the present disclosure. Any two optical fibers chosen among the N optical fibers forming the optical link have refractive index differences Dn_1 and/or Dn_2 and/or Dn_3 at λ_c with values differing by a maximum of $\pm 0.5\times 10^{-3}$ and/or radii R_1 and/or R_{1b} and/or R_2 and/or R_3 with values differing by a maximum of ±0.5µm. Moreover, at least two of said N optical fibers have DMGD with opposite signs, where $DMGD$ is the Differential Mode Group Delay between two guided modes in said optical fiber.

Hence, such an optical link may be formed with optical fibers, which are not exactly identical and show Differential Mode Group Delays with opposite signs, which may compensate each other once assembled in an optical link. Such an optical link is hence a DMGD compensated link. Moreover, a tolerance of ±0.02 on the α, between any combination of optical fibers forming the optical link is also acceptable.

Another aspect of the disclosure concerns an optical system comprising at least one optical fiber or at least one optical link as described here above in any of its embodiments.

5. LIST OF FIGURES

Other features and advantages of embodiments of the present disclosure shall appear from the following description, given by way of an indicative and non-exhaustive examples and from the appended drawings, of which:

- **Figure 1** graphically provides the refractive index profile of a prior art FMF optical fiber supporting 30 LP modes at 1550 nm but in which only 20 LP modes are usable;
- **Figure 2** schematically depicts an isometric view of an exemplary FMF optical fiber according to one or more embodiments described herein;
- **Figure 3** graphically provides the illustrative refractive index profile of FMF optical fibers according to embodiments of the present disclosure;
- **Figure 4** graphically provides the refractive index profile of two exemplary FMF optical fibers according to embodiments of the present disclosure;
- **Figure 5** graphically provides the refractive index profile of two other exemplary FMF optical fibers according to embodiments of the present disclosure;
- **Figure 6** illustrates an optical link according to an embodiment of the present disclosure;
- **Figures 7A and 7B** illustrate embodiments of an optical system according to the present disclosure.

The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the present disclosure.

6. DETAILED DESCRIPTION

The general principle of the present disclosure is to propose a carefully designed trench-assisted graded index few-mode optical fiber, showing reduced Differential Mode Group Delay and supporting more LP modes over prior art FMFs. More precisely, the purpose of such a design is to optimize the interface between the graded-index core and the trench, in order to increase the number of supported LP modes up to 25 or 30, while keeping the Differential Mode Group Delay between any combination of LP guided modes low, preferably below 200 ps/km, and while keeping the bend loss of any LP guided modes low, preferably below 100 dB/turn at 10 mm bend radius.

Light travelling in an optical fiber actually forms hybrid-type modes, which are usually referred to as LP (linear polarization) modes. The LP_{0p} modes have two polarization degrees of freedom and are two-fold degenerate, the LP_{mp} modes with $m \geq 1$ are four-fold degenerate. These degeneracies are not counted when designating the number of LP modes propagating in the fiber. Hence, a few-mode optical fiber having two LP modes supports the propagation of all of the LP_{01} and LP_{11} modes, or a few-mode fiber guiding 6 LP modes supports the propagation of all of the LP_{01}, LP_{11}, LP_{02}, LP_{21}, LP_{12} and LP_{31} modes.

Reference will now be made in detail to embodiments of few-mode optical fibers, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts.

One embodiment of a few-mode optical fiber according to the present disclosure is schematically depicted in isometric view in **Figure 2**. The optical fiber 20 generally has a glass core 21 surrounded by a glass cladding. More precisely, the optical fiber 20 comprises four abutting concentric regions, namely:

- a graded-index core 21, with an outer radius R_{1b};
- an intermediate trench 22, with an inner radius R_{1b} and an outer radius R_2;
- a trench 23, with an inner radius R_2 and an outer radius R_3;
- an outer cladding 24, with an inner radius R_3 and an outer radius R_4 and a refractive index n_{Cl}.

The radii of the intermediate trench 22 and of the trench 23 are such that $R_{1b} < R_2 < R_3$.

In embodiments of the present disclosure, the glass core 21 generally has a radius R_1 at zero refractive index difference (i.e. $n(R_1) = n_{Cl}$) from about 21.5 µm to about 27 µm. Moreover, the trench has an outer radius R_3 between 30 µm and 42 µm. In the embodiments shown and described herein, the core 21 and the cladding generally comprise silica, specifically silica glass. The cross-section of the optical fiber 20 may be generally circular-symmetric with respect to the center of the core 21. In some embodiments described herein, the radius R_4 (i.e. the radius of the glass portion of the optical fiber 10) is about 62.5 µm. However, it should be understood that the dimensions of the cladding may be adjusted such that the radius R_4 may be greater than or less than 62,5 µm. The optical fiber 20 also comprises a coating surrounding the cladding. Such a coating may comprise several layers, and it may notably be a dual-layer coating, although these different layers are not shown on **figure 2**.

The different portions in the cladding may comprise pure silica glass (SiO_2), silica glass with one or more dopants, which increase the index of refraction (e.g. GeO_2 or any other known dopant), such as when the portion of the cladding is “up-doped”, or silica glass with a dopant, which decreases the index of refraction, such as fluorine, such as when the portion of the cladding is “down-doped” (e.g. for the intermediate trench 22 or for the trench 23).

Although not illustrated on figure 2, the outer cladding 24 may also comprise other portions or layers of lower or higher refractive indexes, for $r > R_3$.

It must also be noted that, in some embodiments, it is possible that $R_1 = R_{1b}$.

Figure 3 depicts the refractive index profile n(r) of optical fiber 20 according to an embodiment of the present disclosure. It describes the relationship between the refractive index value n and the distance r from the center of the optical fiber. The x-axis represents radial position with x=0 representing the center of the core region, and the y-axis represents refractive index, expressed as an index difference Dn unless otherwise stated. Throughout this document, refractive index differences are determined at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended. For example, $\lambda_c = 1550nm$.

In this embodiment, the optical fiber 20 has an optical core 21 having a refractive index profile n(r) defined as follows:

$$n(r) = n_0\sqrt{1 - 2\Delta\left(\frac{r}{R_{1b}}\right)^{\alpha}}, r \leq R_{1b}$$

where:

r is a variable representative of the radius of the optical fiber,

R_{1b} is the optical core outer radius,

Δ is the normalized refractive index difference, with $\Delta = \frac{n_0^2 - n_1^2}{2n_0^2}$

n_1 is the minimal refractive index of the optical core,

n_0 is the maximal refractive index of the optical core,

α is a non-dimensional parameter that defines the index profile shape of the optical core.

The alpha refractive index profile of the optical core 21 allows reducing intermodal dispersion of the optical fiber 20. The optical core 21 has a radius R_1, at which the refractive index difference of the core with respect to the cladding is equal to zero, as $n(R_1) = n_{Cl}$, with n_{Cl} the refractive index of the outer cladding. The optical core 21 also has a maximum refractive index difference with the outer cladding 24 $Dn_1 = n_0 - n_{Cl}$ between 12.5x10^{-3} and 20×10^{-3}.

At its outer radius R_{1b}, the optical central core 21 shows a refractive index difference $Dn_{1b} = n(R_{1b}) - n_{Cl}$ with the outer cladding 24. Hence, in embodiments where $R_{1b} > R_1$, the minimal refractive index of the core 21 is not equal to the refractive index of the outer cladding n_{Cl} but shows a negative refractive index difference Dn_{1b} with respect to the optical fiber outer cladding.

In some other embodiments, $R_1 = R_{1b}$, and the minimal refractive index of the core 21 is equal to the refractive index of the outer cladding n_{Cl}.

The optical core 21 is directly surrounded by an optical cladding, which comprises an intermediate depressed-index region 22, also called an intermediate trench, with inner radius R_{1b} and outer radius R_2, a depressed-index ring 23, also called a trench, with inner radius R_2 and outer radius R_3, and an outer cladding layer 24 with inner radius R_3. In some embodiments such an outer cladding layer 24 comprises pure silica glass (SiO_2) and its refractive index n_{Cl} is hence that of silica glass.

The intermediate trench 22 has a negative refractive index difference Dn_2 with respect to the refractive index of the outer cladding, and the trench 23 has a negative refractive index difference $Dn_3 = n_{trench} - n_{Cl}$ comprised between -15x10^{-3} and -6x10^{-3}, such that $Dn_3 < Dn_2 < 0$. Their position and size are designed so as to improve bend-loss resistance of the fiber. Notably, their design is such that:

- for $|Dn_{1b} - Dn_2| \geq 0.5\times10^{-3}$, $Min(Dn_{1b}, Dn_2) \leq -1.5\times10^{-3}$, and
- for $|Dn_{1b} - Dn_2| < 0.5\times10^{-3}$, Dn_2 is between -5×10^{-3} and -3.5×10^{-3}.

The careful design of such an intermediate trench 22, associated with the trench 23, allows forming an optimized specific interface between the central optical core and the cladding, and thus allows achieving Few-Mode Fibers, which support 25 or 30 LP guided modes.

Their normalized frequency $V = \frac{2\pi R_1}{\lambda_c}\sqrt{n_0^2 - n_{Cl}^2}$ (where λ_c is the operating wavelength of the fiber) is between 18.4 and 23.

Max|DMGD| (i.e. the absolute maximum value of the Differential Mode Group Delay between two guided modes in said optical fiber) between any combination of LP guided modes is below 200ps/km, at λ, here 1550nm (and more generally at $\lambda = \lambda_C$, where λ_C is the central wavelength of any operating band for which the optical fiber is intended). Max|DMGD| is also preferably <500ps/km from 1530 to 1570nm (and more generally for any operating wavelength band $[\lambda_C - \delta\lambda; \lambda_C + \delta\lambda]$ where $2\delta\lambda$ is a width of said operating band, preferably $\delta\lambda$=20nm, such as the C-band, or the L-, S-, or U-band for example).

All LP guided modes of FMFs according to an embodiment of the present disclosure have bend losses <100dB/turn, preferably <50dB/turn, at 10mm bend radius at 1550nm (and more generally at $\lambda = \lambda_C$, where λ_C is the central wavelength of any operating band for which the optical fiber is intended). Moreover, the effective area A_{eff} of the fundamental LP_{01} mode, which is the smallest effective area of all LP guided modes, is $> 150\mu m^2$ at 1550nm (and more generally at $\lambda = \lambda_C$, where λ_C is the central wavelength of any operating band for which the optical fiber is intended). As used herein, the effective area of an optical fiber is the area of the optical fiber in which light is propagated and is determined at the specified mode (e.g. LP_{01}), at a wavelength of 1550nm, unless otherwise specified.

Table 1 gives the parameters of the index profiles of twelve examples of FMFs according to the embodiment of **Figures 2 and 3** (Ex. 1 to Ex. 12), and results on the normalized frequency V, Max|DMGD|, Max|BL|, and effective area A_{eff}.

Table 1:

	Comp. Ex.	Ex.1	Ex.2	Ex.3	Ex.4	Ex.5	Ex.6	Ex.7	Ex.8	Ex.9	Ex.10	Ex.11	Ex.12
Number of guided LP modes	30	25				30		25	30		25	30	
Alpha	1.940	1.94	1.94	1.94	1.94	1.93	1.93	1.94	1.93	1.94	1.91	1.92	1.92
R1 (µm)	25.00	23.1	22.9	22.5	25.0	21.6	21.6	22.2	22.5	22.5	22.8	25.0	25.0
Dn1 ($x10^3$ at 1550nm)	15.8	15.8	15.8	15.8	12.8	18.7	19.8	14.5	17.1	17.1	13.6	16.0	15.8
R1b (µm)	=R1	25.0	25.0	25.0	26.9	22.2	22.7	25.0	25.0	25.0	=R1	=R1	=R1
Dn1b ($x10^3$ at 1550nm)	/	-2.6	-3.0	-3.6	-1.9	-1.0	-1.9	-3.9	-3.9	-3.9	0.0	0.0	0.0
R2 (µm)	26.16	25.8	26.1	26.1	29.5	25.7	25.7	25.8	25.7	26.0	28.8	31.0	31.0
Dn2 ($x10^3$ at 1550nm)	0.00	-1.2	-1.0	-1.9	-2.9	-2.9	-3.9	=Dn1b	=Dn1b	=Dn1b	-1.9	-1.9	-1.9
R3 (µm)	30.56	32.5	32.9	33.1	38.3	33.4	33.4	33.6	33.4	33.7	37.4	40.3	40.3
Dn3 ($x10^3$ at 1550nm)	-6.60	-6.6	-9.6	-9.6	-6.7	-6.7	-6.7	-6.7	-6.7	-7.7	-6.7	-6.7	-8.7
V	21.7	20.1	19.9	19.5	19.6	20.4	21.0	18.4	20.4	20.4	18.4	21.8	21.7
Max|DMGD| (ps/km)	>500	53	52	55	61	133	142	60	89	87	195	190	195
Max|BL| (dB/turn)	>1000	72	6	4	9	14	7	10	20	9	1	30	29
Aeff LP_{01} (µm²)	175	162	161	158	196	139	135	163	152	152	171	172	172

As may be observed, twelve examples of FMFs according to embodiments of the present disclosure are given, and compared, in the first column of **Table 1**, with a comparative example Comp. Ex., corresponding to a multimode fiber, which would have been adapted to be used at $\lambda = 1550nm$, rather than $\lambda = 850nm$ as is usually the case for standard multimode fibers. Such an adaptation is performed by modifying the value of α for the graded-index profile of the core, which is around 1.94, rather than $\alpha = 2.0$ as is usually the case for standard MMFs.

For such a comparative example, the core radius is classically $R_1 = 25\mu m$, and the graded-index profile of the core is such that the minimal refractive index of the core is equal to the refractive index of the outer cladding. In other words, $R_1 = R_{1b}$. Moreover, there is no intermediate trench 22, and Dn_2=0. In other words, there is no specific design of the interface between the optical core and the cladding, which results in very high values of both the maximum Differential Mode Group delays and the maximum bend losses, as Max|DMGD|>500ps/km and Max|BL|>1000dB/turn.

Such a fiber (Comp. Ex) may hence not be used as a Few Mode Fiber for Mode Division Multiplexing.

Examples Ex.1 to Ex. 4, Ex. 7 and Ex. 10 correspond to FMFs supporting 25 LP guided modes, while examples Ex. 5, Ex. 6, Ex. 8, Ex. 9, Ex. 11 and Ex. 12 correspond to FMFs supporting 30 LP guided modes.

Examples Ex. 10 to Ex. 12 correspond to a peculiar embodiment where $R_1=R_{1b}$, and the minimal refractive index of the optical core 21 is equal to the refractive index n_{Cl} of the outer cladding 24.

Examples Ex. 7 to Ex. 9 correspond to another peculiar embodiment, where $Dn_2=Dn_{1b}$, i.e. the refractive index of the intermediate trench 22 is equal to the minimal refractive index of the core 21.

Moreover, examples Ex. 1 to Ex. 6 and Ex. 10 to Ex. 12 correspond to a specific design of the interface between the core and the cladding, which is such that $|Dn_{1b} - Dn_2| \geq 0.5\times10^{-3}$, and $Min(Dn_{1b}, Dn_2) \leq -1.5\times10^{-3}$.

Examples Ex. 7 to Ex. 9 correspond to another specific design of the interface between the core and the cladding, which is such that $|Dn_{1b} - Dn_2| < 0.5\times10^{-3}$ and Dn_2 is between -5×10^{-3} and -3.5×10^{-3}.

Figure 4 graphically provides the refractive index profile of two exemplary FMF optical fibers, corresponding to examples Ex. 1 and Ex. 6 in **Table 1**. The refractive index difference Dn shown on the y-axis is measured at 1550nm, and the radius of the FMF fiber shown on the x-axis is expressed in μm.

The refractive index difference of the FMF of example Ex. 6 is shown in dashed lines. The graded-index core 21 shows a α-profile with α=1.93, a radius R_1=21.6μm at 0 refractive index difference and a maximum refractive index difference $Dn_1=19.8\text{x}10^{-3}$ at 1550nm. The α-profile ends at R_{1b}=22.7μm, with index difference $Dn_{1b}=-1.9\text{x}10^{-3}$.

An intermediate trench 22 is down-doped as compared to the optical core 21 and shows a refractive index difference with the outer cladding 24 $Dn_2=-3.9\text{x}10^{-3}$. It ends at radius R_2=25.7μm. It is surrounded by a trench 23, which is down-doped as compared to the intermediate trench 22, and shows a refractive index difference with the outer cladding 24 $Dn_3=-6.7\text{x}10^{-3}$ at 1550nm. It ends at radius R_3=33.4μm.

For this example, as indicated in **table 1**, we have V=21.0, Max|DMGD|=142ps/km, Max|BL|=7dB/turn and A_{eff}=135μm^2 for the LP_{01} guided mode.

The refractive index difference of the FMF of example Ex. 1 is shown in solid lines. The graded-index core 21 shows a α-profile with α=1.94, a radius R_1=23.1μm at 0 refractive index difference and a maximum refractive index difference $Dn_1=15.8\text{x}10^{-3}$ at 1550nm. The α-profile ends at R_{1b}=25.0μm, with index difference $Dn_{1b}=-2.6\text{x}10^{-3}$.

An intermediate trench 22 is up-doped as compared to minimal refractive index of the optical core 21 and shows a refractive index difference with the outer cladding 24 $Dn_2=-1.2\text{x}10^{-3}$. It ends at radius R_2=25.8μm. It is surrounded by a trench 23, which is down-doped as compared to the intermediate trench 22, and shows a refractive index difference with the outer cladding 24 Dn_3=-6.6x10^{-3} at 1550nm. It ends at radius R_3=32.5 μm.

For this example, as indicated in **table 1**, we have V=20.1, Max|DMGD|=53ps/km, Max|BL|=72dB/turn and A_{eff}=162μm^2 for the LP_{01} guided mode.

Figure 5 graphically provides the refractive index profile of two other exemplary FMF optical fibers, corresponding to examples Ex. 8 and Ex. 10 in **Table 1**. The refractive index difference Dn shown on the y-axis is measured at 1550nm, and the radius of the FMF fiber shown on the x-axis is expressed in μm.

The refractive index difference of the FMF of example Ex. 8 is shown in grey lines. The graded-index core 21 shows a α-profile with α=1.93, a radius R_1=22.5μm at 0 refractive index difference and a maximum refractive index difference Dn_1=17.1x10^{-3} at 1550nm. The α-profile ends at R_{1b}=25.0 μm, with index difference Dn_{1b}=-3.9x10^{-3}.

An intermediate trench 22 has a refractive index, which is equal to the minimal refractive index of the optical core 21, and hence shows a refractive index difference with the outer cladding 24 Dn_2=Dn_{1b}=-3.9x10^{-3}. It ends at radius R_2=25.7 μm. It is surrounded by a trench 23, which is down-doped as compared to the intermediate trench 22, and shows a refractive index difference with the outer cladding 24 Dn_3=-6.7x10^{-3} at 1550nm. It ends at radius R_3=33.4 μm.

For this example, as indicated in **table 1**, we have V=20.4, Max|DMGD|=89ps/km, Max|BL|=20dB/turn and A_{eff}=152μm^2 for the LP_{01} guided mode.

The refractive index difference of the FMF of example Ex. 10 is shown in black solid lines. The graded-index core 21 shows a α-profile with α=1.91, a radius R_1=22.8μm at 0 refractive index difference and a maximum refractive index difference Dn_1=13.6x10^{-3} at 1550nm. The α-profile ends at R_1=R_{1b}, with a zero refractive index difference with respect to the outer cladding.

An intermediate trench 22 is down-doped as compared to the outer cladding 24 and shows a refractive index difference with the outer cladding 24 Dn_2=-1.9x10^{-3}. It ends at radius R_2=28.8 μm. It is surrounded by a trench 23, which is down-doped as compared to the intermediate trench 22, and shows a refractive index difference with the outer cladding 24 Dn_3=-6.7x10^{-3} at 1550nm. It ends at radius R_3=37.4 μm.

For this example, as indicated in **table 1**, we have V=18.4, Max|DMGD|=195ps/km, Max|BL|=1dB/turn and A_{eff}=171μm^2 for the LP_{01} guided mode.

Figure 6 illustrates an optical link 60 according to an embodiment of the present disclosure. Such an optical link comprises p spans of optical fibers, with $p \geq 2$, which are spliced together. **Figure 6** only shows optical fiber 60_1 and optical fiber 60_p, all the other potential optical fibers in the optical link being symbolized by dashed lines. At least one of the optical fibers in optical link 60 is such that it comprises the features of one embodiment described above. In other words, at least one of the optical fibers supports 25 or 30 LP guided modes and shows the specific design of the interface between the core and the cladding described above in relation to **figures 2 to 5**, and notably:

- A graded index core with a α-profile with α between 1 and 3, a radius R_1 (at 0 refractive index difference) between 21.5 and 27µm and a maximum refractive index difference Dn_1 between $12.5\text{x}10^{-3}$ and $20\text{x}10^{-3}$, and an end of the α-profile at a radius R_{1b}, with index difference Dn_{1b} ;
- A trench surrounding the core with radius R_3 between 30 and 42µm and refractive index difference Dn_3 between -15.10^{-3} and -6.10^{-3},
- An intermediate depressed trench with a radius R_2, with $R_{1b}<R_2<R_3$ and a refractive index difference Dn_2, with $Dn_3<Dn_2<0$, and a specific design of the refractive index differences of these different parts of the FMF such that:
  - ○For $|Dn_{1b}-Dn_2|>=0.5\text{x}10\text{-}3$, $\text{Min}(Dn_{1b}, Dn_2) \leq -1.5\text{x}10\text{-}3$, and for:
  - ○$|Dn_{1b}-Dn_2|<0.5\text{x}10\text{-}3$, Dn_2 is between -5x10-3 and -3.5x10-3.

However, optical link 60 may also be such that several or all the optical fibers it comprises comply with an embodiment of the present disclosure.

In a specific embodiment, optical link 60 is made up of several spans of FMFs, which show DMGD with opposite signs, and which are combined in a same optical link. For example, the spans of FMFs used correspond to FMFs which all meet the criteria and performance described above for FMFs according to embodiments of the present disclosure, but which actual criteria diverge from each other, either on purpose, or because of process variations during manufacturing. For example, considering any pair of fibers forming the optical link, the refractive index differences at 1550nm achieved for Dn_1, Dn_2 and Dn_3 may differ by no more than $\pm 0.5\times 10^{-3}$, the radii R_1, R_{1b}, R_2 and R_3 may differ by no more than ±0.5µm, and the α-value may differ by no more than ±0.02 between any combination of fibers forming the optical link. In other words, the purpose of such an optical link is, among others, to compensate for small profile variations that can occur during the manufacturing process of a few-mode fiber by concatenating several FMFs showing different features.

Actually, there are optimum values for α, for which Max|DMGD| have minimum values, and α lower and higher than these "optimum α" generally exhibit DMGDs with opposite signs.

As a consequence, the inventors have reached the conclusion that, if a FMF is off-target in term of α (i.e. if the α-value of the FMF is either slightly higher or lower than the "optimum α", for example in the order of ±0.02), it is possible to associate it with another FMF showing an appropriate α (i.e. either higher than the “optimum α” if the off-target α is smaller, or smaller than the “optimum α” if the off-target α is higher), by choosing the appropriate lengths for both FMFs, in order to realize a “DMGD-compensated” link.

This association can, for instance, compensate for process variability that may result in FMFs with slightly off-optimum Alphas.

Optical fiber link 60 has a length of L km, which can be of several tens or several hundreds of kilometers. In an example there are at least two spans of fiber 60_1 and 60_2. In another example, there are at least five spans of fibers 60_1 to 60_5. In yet another example, there are at least ten spans of fiber 60_1 to 60_{10}.

In other words, few-mode fibers 1 to p are spliced together to form an optical link 60 of length $L = L_1 + \cdots + L_i + \cdots + L_p$, which can be of several tens or several hundreds of kilometers.

The lengths L_i of the different spans of fibers are chosen so as to minimize the maximum DMGD on the optical link, and so that the optical link shows link parameters which fulfill the requirements set forth above for FMF fibers in relation to embodiments of the present disclosure, namely:

- an average optical core radius R_{1link} comprised between 21.5 µm and 27 µm, where $R_{1link} = \frac{\sum_{i=1}^{N} R_{1i} L_i}{\sum_{i=1}^{N} L_i}$ with L_i the length of optical fiber i in the link,
- an average maximum refractive index difference Dn_{1link} between $12.5\text{x}10^{-3}$ and $20\text{x}10^{-3}$, where $Dn_{1link} = \frac{\sum_{i=1}^{N} Dn_{1i} L_i}{\sum_{i=1}^{N} L_i}$, at $\lambda = 1550nm$,
- an average trench outer radius R_{3link} between 30 µm and 42 µm, where $R_{3link} = \frac{\sum_{i=1}^{N} R_{3i} L_i}{\sum_{i=1}^{N} L_i}$,
- an average refractive index difference between the trench and the cladding Dn_{3link} comprised between $-15\text{x}10^{-3}$ and $-6\text{x}10^{-3}$, at $\lambda = 1550nm$, where $Dn_{3link} = \frac{\sum_{i=1}^{N} Dn_{3i} L_i}{\sum_{i=1}^{N} L_i}$,
- for $|Dn_{1blink} - Dn_{2link}| \geq 0.5\times10^{-3}$, $Min(Dn_{1blink}, Dn_{2link}) \leq -1.5\times10^{-3}$, and
- for $|Dn_{1blink} - Dn_{2link}| < 0.5\times10^{-3}$, Dn_{2link} is between -5×10^{-3} and -3.5×10^{-3}

where $Dn_{2link} = \frac{\sum_{i=1}^{N} Dn_{2i} L_i}{\sum_{i=1}^{N} L_i}$ is the average refractive index difference between the intermediate trench and the cladding for the optical link and where $Dn_{1blink} = \frac{\sum_{i=1}^{N} Dn_{1bi} L_i}{\sum_{i=1}^{N} L_i}$ is the average refractive index difference between the core at its outer radius and the cladding for the optical link, both at $\lambda = 1550nm$.

These DMGD-compensated links, supporting 25 or 30 LP guided modes, have Max|DMGD|<100ps/km at $\lambda = 1550nm$ (and more generally at $\lambda = \lambda_C$, where λ_C is the central wavelength of any operating band for which the optical fiber is intended) and <300ps/km from

1530 to 1570nm (and more generally for any operating wavelength band $[\lambda_C - \delta\lambda;\ \lambda_C + \delta\lambda]$ where $2\delta\lambda$ is a width of said operating band, preferably $\delta\lambda$=20nm, such as the C-band, or the L-, S-, or U-band for example).

Figures 7A and 7B illustrate embodiments of an optical system according to the present disclosure.

According to the first embodiment in **figure 7A**, such an optical system comprises transceivers 71 and receivers 75 optically connected by an optical fiber link 60 that includes at least one span of fiber. Transceivers 71 comprise light sources (such as lasers) and generate n LP modes, referenced 1, 2, ..., n used in the optical system of **figure 7A**. A mode multiplexer 72 multiplexes the n LP modes and is optically connected to optical link 60, which guides the n multiplexed LP modes, towards a mode demultiplexer 73, which is optically connected to the end of optical link 60.

Mode demultiplexer 73 demultiplexes the n multiplexed LP modes, and feeds each LP mode into an amplifier 74. At the output of amplifiers 74, LP modes enter receivers 75.

Such an optical system may comprise M optical links (or M spans of optical fibers). In an example, M=1; in another example, M=2; in another example M=5; in yet another example, M=10. In case the optical system comprises M optical links or spans, it also comprises M mode multiplexers 72, M mode demultiplexers 73, and M amplifiers 74 for each LP mode guided by the optical system.

The embodiment in **figure 7B** differs from the first embodiment in **figure 7A** in that amplifier 74 amplifies all LP modes guided by the optical fiber 60; as such, amplifier 74 is optically connected between the output of optical link 60 and the input of mode demultiplexer 73. In this second embodiment, when the optical system comprises M optical links or spans, it also comprises M amplifiers 74; however, there is only one mode multiplexer 72, optically connected between transceivers 71 an optical link 60, and only one mode demultiplexer 73, optically connected between amplifier 74 and receivers 75.

The embodiments of **figures 7A and 7B** are given as mere examples, and an optical fiber according to the present disclosure may of course be used in any other kind of optical system.

CLAIMS

1. Optical fiber comprising a central optical core surrounded by an optical cladding,

said optical core having a α graded-index profile $n(r)$ with α between 1 and 3, α being a non-dimensional parameter that defines an index profile shape of said optical core, that is a function of a radial distance r from the center of said optical core,

said optical core having a maximum refractive index n_0 and an outer radius R_{1b} with a refractive index difference $Dn_{1b} = n(R_{1b}) - n_{Cl}$ with respect to said optical cladding having at its outer edge a refractive index n_{Cl},

said optical core having a radius R_1, such that $n(R_1) = n_{Cl}$, comprised between 21.5 µm and 27 µm and a maximum refractive index difference $Dn_1 = n_0 - n_{Cl}$ between 12.5x10^{-3} and 20×10^{-3},

said refractive index difference being determined at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended,

said optical cladding comprising:

- a region of depressed refractive index n_{trench}, called a trench, surrounding the optical core, said trench having an outer radius R_3 between 30 µm and 42 µm, and a refractive index difference $Dn_3 = n_{trench} - n_{Cl}$ between the trench and the cladding comprised between -15x10^{-3} and -6x10^{-3};
- an intermediate region of depressed refractive index, called an intermediate trench, surrounding the optical core, said intermediate trench having an outer radius R_2, with $R_{1b} < R_2 < R_3$, and a refractive index difference Dn_2 between the intermediate trench and the cladding, with $Dn_3 < Dn_2 < 0$,

wherein:

- for $|Dn_{1b} - Dn_2| \geq 0.5\times10^{-3}$, $Min(Dn_{1b}, Dn_2) \leq -1.5\times10^{-3}$, and
- for $|Dn_{1b} - Dn_2| < 0.5\times10^{-3}$, Dn_2 is between -5×10^{-3} and -3.5×10^{-3}.

2. Optical fiber according to claim 1, wherein its normalized frequency $V = \frac{2\pi R_1}{\lambda_c}\sqrt{n_0^2 - n_{Cl}^2}$ is between 18.4 and 23.

3. Optical fiber according to claim 1 or 2, wherein it guides at least 25 LP modes.

4. Optical fiber according to any of claims 1 to 3, wherein it guides at least 30 LP modes.

5. Optical fiber according to any of claims 1 to 4, wherein $Max|DMGDs| < 200ps/km$ at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended, where $DMGD$ is the Differential Mode Group Delay between two guided modes in said optical fiber, and where Max|DMGDs| is the absolute maximum value of DMGD between any combination of guided modes.

6. Optical fiber according to claim 5, wherein $Max|DMGDs| < 500ps/km$ for $\lambda \epsilon [\lambda_C - \delta\lambda;\ \lambda_C + \delta\lambda]$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended and where $2\delta\lambda$ is a width of said operating band.

7. Optical fiber according to any of claims 1 to 6, wherein the fundamental LP_{01} mode guided by said optical fiber has an effective area A_{eff}>150µm^2 at $\lambda = \lambda_C$.

8. Optical fiber according to any of the previous claims, wherein $Max|BL| < 100dB/turn$, preferably <50dB/turn, at 10mm bend radius at $\lambda = \lambda_C$, where BL are the bend losses of the different guided modes in said optical fiber, and where $Max|BL|$ is the absolute maximum value of BL for all guided modes.

9. Optical fiber according to any of claims 1 to 8, wherein λ_c=1550 nm and $\delta\lambda$= 20 nm.

10. Optical link comprising at least one optical fiber according to any of claims 1 to 9.

11. Optical link comprising N optical fibers, with $N \geq 2$, N being an integer,

each optical fiber of index $i \in [\![1;N]\!]$ comprising a central optical core and an optical cladding surrounding the optical core, the optical core having a α_i graded-index profile $n_i(r)$ with α_i between 1 and 3, α_i being a non-dimensional parameter that defines an index profile shape of the optical core, that is a function of a radial distance r from the center of said optical core,

and the optical core having a maximal refractive index n_{0i}, and an outer radius R_{1bi} with a refractive index difference $Dn_{1bi} = n_i(R_{1bi}) - n_{Cli}$ with respect to said optical cladding having at its outer edge a refractive index n_{Cli}, said optical core also having a radius R_{1i}, such that $n_i(R_{1i}) = n_{Cli}$, and a maximum refractive index difference $Dn_{1i} = n_{0i} - n_{Cli}$,

said optical cladding comprising:

- a region of depressed refractive index $n_{trenchi}$, called a trench, surrounding the optical core, said trench having an outer radius R_{3i}, and a refractive index difference $Dn_{3i} = n_{trenchi} - n_{Cli}$ between the trench and the cladding;
- an intermediate region of depressed refractive index, called an intermediate trench, surrounding the optical core, said intermediate trench having an outer radius R_{2i}, with $R_{1bi} < R_{2i} < R_{3i}$, and a refractive index difference Dn_{2i} between the intermediate trench and the cladding, with $Dn_{3i} < Dn_{2i} < 0$,

wherein an average optical core radius R_{1link} for said optical link is comprised between 21.5 µm and 27 µm, where $R_{1link} = \frac{\sum_{i=1}^{N} R_{1i}L_i}{\sum_{i=1}^{N} L_i}$ with L_i a length of optical fiber i in said link, an average maximum refractive index difference Dn_{1link} for said optical link is between 12.5x10^{-3} and 20x10^{-3}, where $Dn_{1link} = \frac{\sum_{i=1}^{N} Dn_{1i}L_i}{\sum_{i=1}^{N} L_i}$, at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended,

an average trench outer radius R_{3link} for said optical link is between 30 µm and 42 µm, where $R_{3link} = \frac{\sum_{i=1}^{N} R_{3i}L_i}{\sum_{i=1}^{N} L_i}$ with L_i a length of optical fiber i in said link,

an average refractive index difference between the trench and the cladding Dn_{3link} for said optical link is comprised between -15x10^{-3} and -6x10^{-3}, at $\lambda = \lambda_C$, where $Dn_{3link} = \frac{\sum_{i=1}^{N} Dn_{3i}L_i}{\sum_{i=1}^{N} L_i}$,

and wherein:

- for $|Dn_{1blink} - Dn_{2link}| \geq 0.5\times10^{-3}$, $Min(Dn_{1blink}, Dn_{2link}) \leq -1.5\times10^{-3}$, and
- for $|Dn_{1blink} - Dn_{2link}| < 0.5\times10^{-3}$, Dn_{2link} is between -5×10^{-3} and -3.5×10^{-3}

where $Dn_{2link} = \frac{\sum_{i=1}^{N} Dn_{2i}L_i}{\sum_{i=1}^{N} L_i}$ is the average refractive index difference between the intermediate trench and the cladding for said optical link and where $Dn_{1blink} = \frac{\sum_{i=1}^{N} Dn_{1bi}L_i}{\sum_{i=1}^{N} L_i}$ is the average refractive index difference between the core at its outer radius and the cladding for said optical link, both at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical link is intended.

12. Optical link according to claim 11, wherein its normalized frequency $V_{link} = \frac{2\pi R_{1link}}{\lambda_c}\sqrt{n_{0link}^2 - n_{Cllink}^2}$ is between 18.4 and 23, where $n_{0link} = \frac{\sum_{i=1}^{N} n_{0i}L_i}{\sum_{i=1}^{N} L_i}$ is the average maximum refractive index of the core for said optical link, and where $n_{Cllink} = \frac{\sum_{i=1}^{N} n_{Cli}L_i}{\sum_{i=1}^{N} L_i}$ is the average refractive index of the cladding for said optical link.

13. Optical link according to any of claims 11 and 12, wherein it guides at least 25 LP modes.

14. Optical link according to any of claims 11 to 13, wherein it guides at least 30 LP modes.

15. Optical link according to any of claims 11 to 14, wherein for all optical fibers $i \in [\![1; N]\!]$ in said link, said lengths L_i are chosen so as to minimize $Max|DMGD_{link}|$ on said link, where $DMGD_{link}$ is the Differential Mode Group Delay between two guided modes in said optical link, and where Max|DMGD$_{link}$| is the absolute maximum value of Differential Mode Group Delay between any combination of guided modes in said optical link.

16. Optical link according to any of claims 11 to 15, wherein at least two optical fibers in said link have $DMGD_i$ showing opposite signs for at least one mode guided by said optical fibers, where $DMGD_i$ is the Differential Mode Group Delay between said one mode and any other guided mode in optical fiber i.

17. Optical link according to claim 15, wherein $Max|DMGD_{link}| < 200ps/km$ at $\lambda = \lambda_C$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended.

18. Optical link according to claim 17, wherein $Max|DMGD_{link}| < 500ps/km$ for $\lambda\epsilon[\lambda_C - \delta\lambda;\ \lambda_C + \delta\lambda]$, where λ_c is a central transmission wavelength of an operating band for which said optical fiber is intended and where $2\delta\lambda$ is a width of said operating band.

19. Optical link according to any of claims 11 to 18, wherein $Max|BL_{link}| < 100dB/turn$, preferably <50dB/turn, at 10mm bend radius at $\lambda = \lambda_C$, where BL_{link} are the bend losses of the different guided modes in said optical link, and where $Max|BL_{link}|$ is the absolute maximum value of BL_{link} for all guided modes in said optical link.

20. Optical link according to any of claims 11 to 19, wherein λ_c=1550 nm and $\delta\lambda$= 20 nm.

21. Optical link comprising N optical fibers according to any of claims 1 to 20, with $N \geq 2$, N being an integer,

wherein any two optical fibers chosen among said N optical fibers forming said optical link have refractive index differences Dn_1 and/or Dn_2 and/or Dn_3 at λ_c with values differing by a maximum of $\pm 0.5\times10^{-3}$ and/or radii R_1 and/or R_{1b} and/or R_2 and/or R_3 with values differing by a maximum of ±0.5µm,

and wherein at least two of said N optical fibers have DMGD with opposite signs, where $DMGD$ is the Differential Mode Group Delay between two guided modes in said optical fiber.

22. Optical system comprising at least one optical fiber according to any one of claims 1 to 10 or at least one optical link according to any of claims 11 to 21.

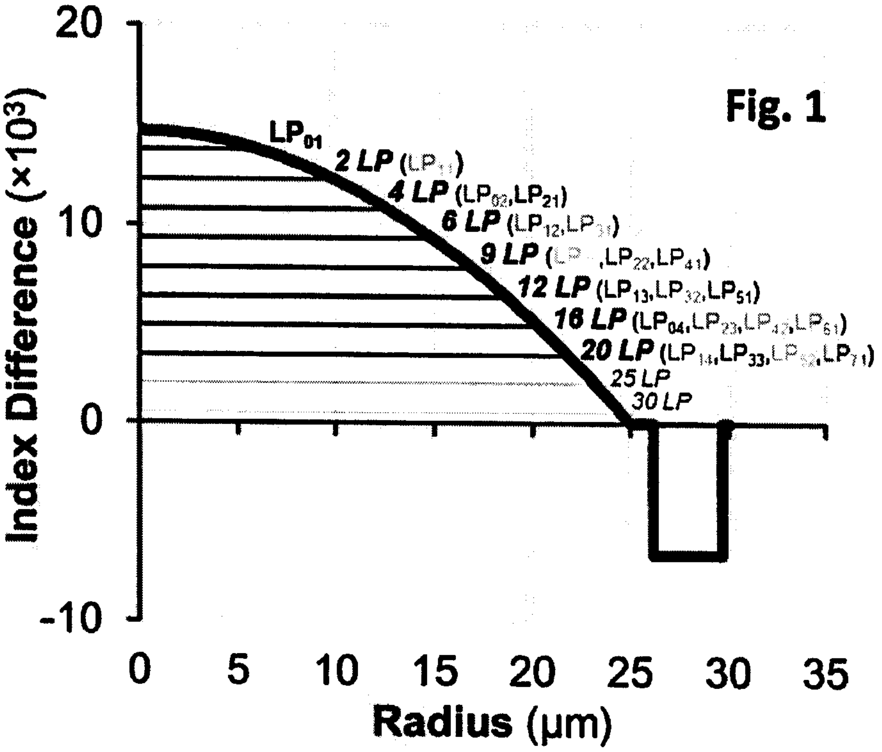
Fig. 1
20
10
0
-10
Index Difference (×10^3)
0
5
10
15
20
25
30
35
Radius (µm)
LP_{01}
2 LP (LP_{11})
4 LP (LP_{02},LP_{21})
6 LP (LP_{12},LP_{31})
9 LP (LP ,LP_{22},LP_{41})
12 LP (LP_{13},LP_{32},LP_{51})
16 LP (LP_{04},LP_{23},LP_{42},LP_{61})
20 LP (LP_{14},LP_{33},LP_{52},LP_{71})
25 LP
30 LP

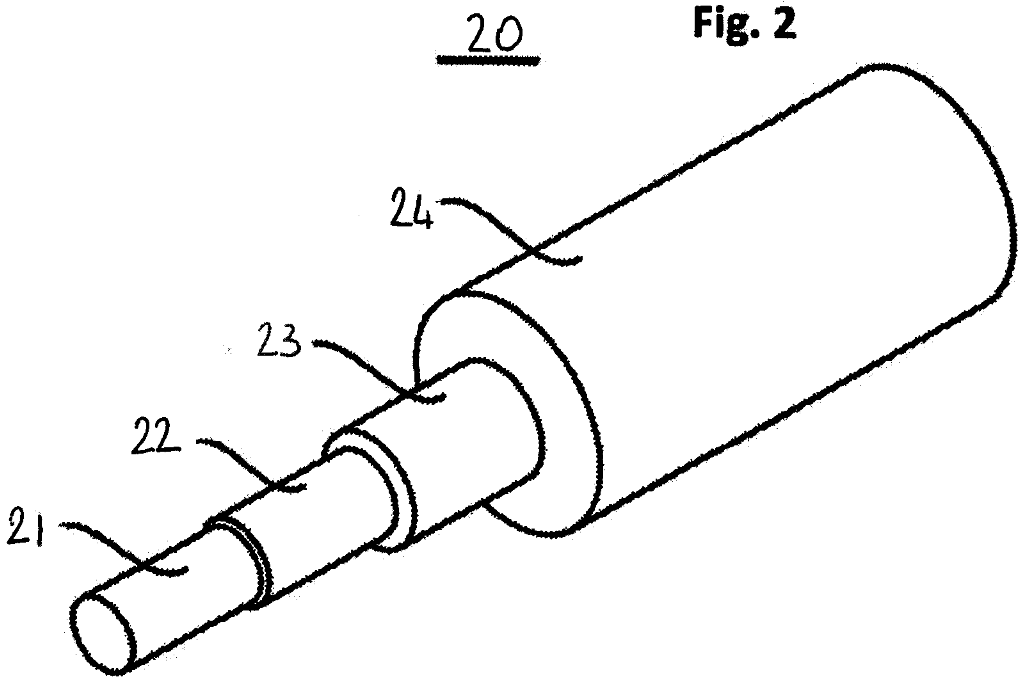
Fig. 2
20
24
23
22
21

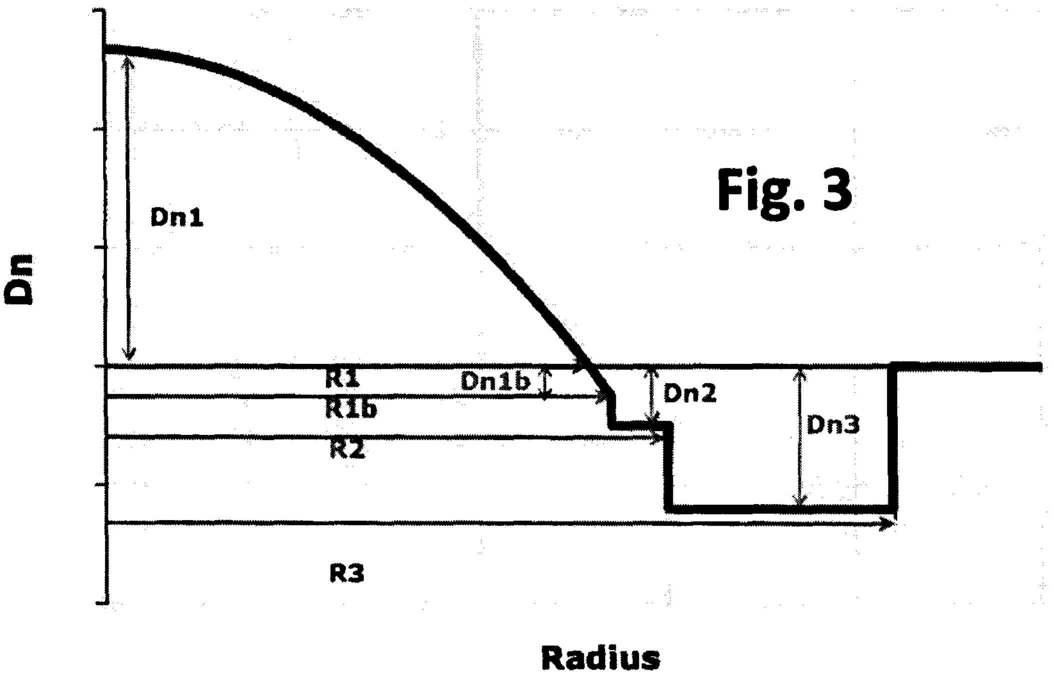

Fig. 3

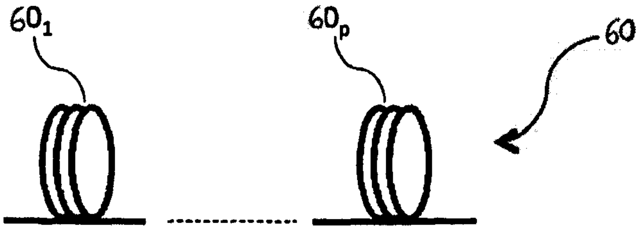

Figure 6

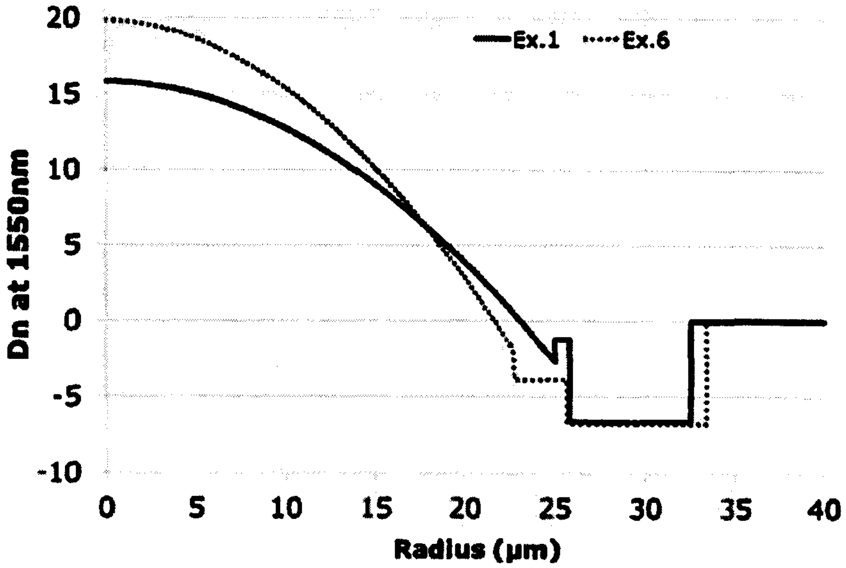
20
15
10
5
0
-5
-10
Dn at 1550nm
0
5
10
15
20
25
30
35
40
Radius (µm)
Ex.1
Ex.6

Fig. 4

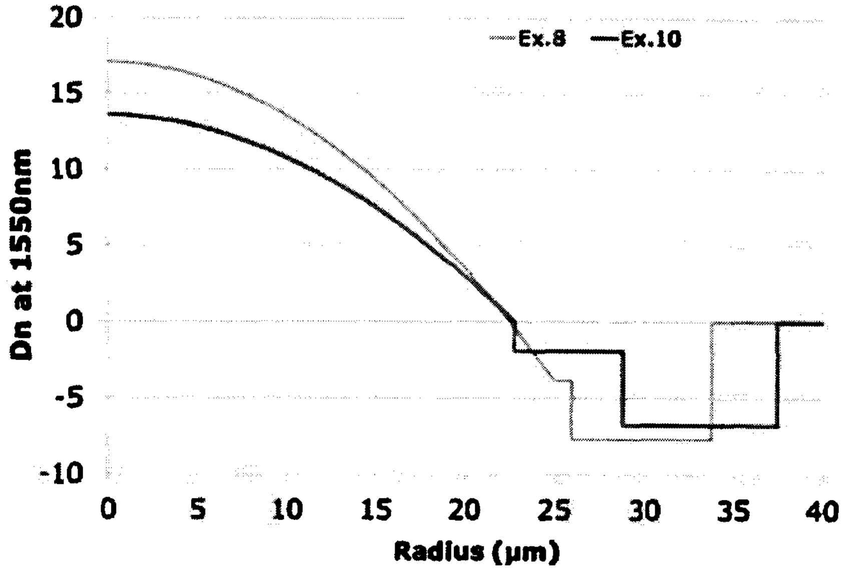
20
15
10
5
0
-5
-10
Dn at 1550nm
0
5
10
15
20
25
30
35
40
Radius (µm)
Ex.8
Ex.10

Fig. 5

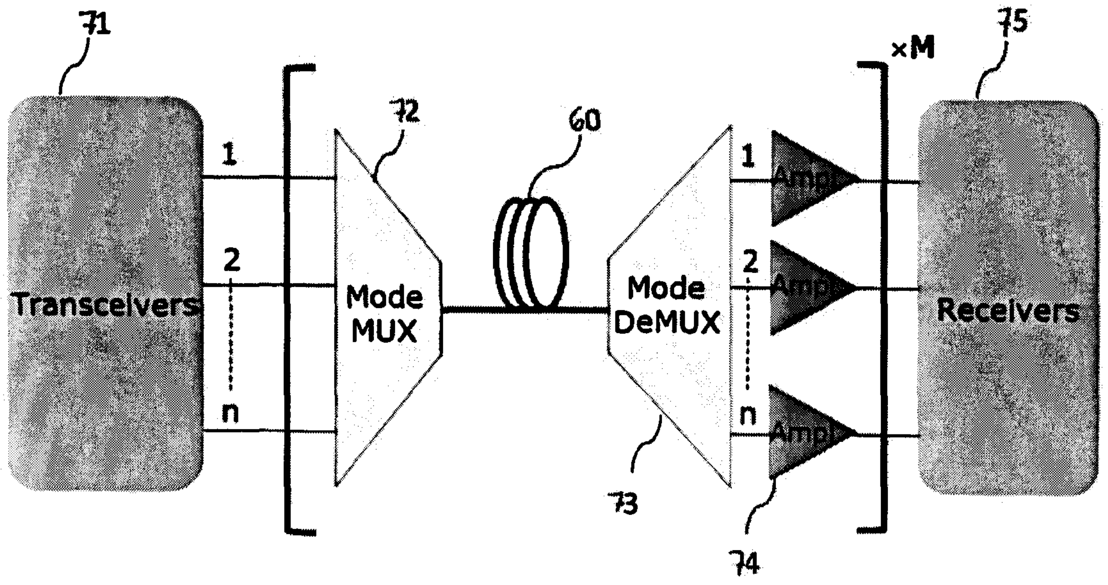
71
Transceivers
1
2
n
72
Mode MUX
60
Mode DeMUX
73
1
2
n
Ampl
Ampl
Ampl
74
×M
75
Receivers

Fig. 7A

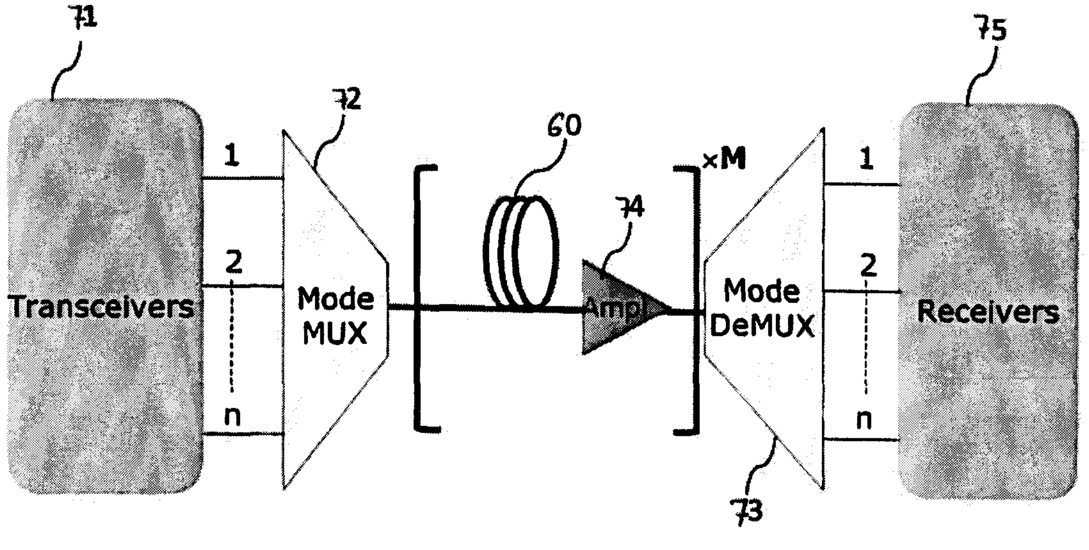
71
Transceivers
1
2
n
72
Mode MUX
60
74
Ampl
×M
Mode DeMUX
73
1
2
n
75
Receivers

Fig. 7B

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2016/001018

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B6/028 G02B6/036
ADD.

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)
G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013/230289 A1 (HAEMMERLE WOLFGANG [DE] ET AL) 5 September 2013 (2013-09-05) the whole document -----	1-22
A	US 2012/294576 A1 (LI MING-JUN [US]) 22 November 2012 (2012-11-22) the whole document -----	1-22
A	WO 2013/126254 A1 (CORNING INC [US]; BICKHAM SCOTT ROBERTSON [US]; LI MING-JUN [US]; LI S) 29 August 2013 (2013-08-29) the whole document -----	10-22

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search 26 October 2016	Date of mailing of the international search report 05/12/2016
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Albayrak, Charlotte

INTERNATIONAL SEARCH REPORT

Information on patent family members

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PCT/IB2016/001018

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