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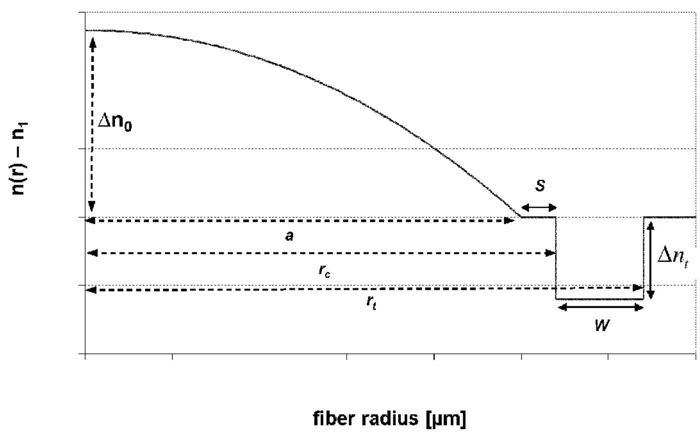

Figure 1

(57) **Abstract**: The invention relates to a multimode optical fiber comprising an optical core and an optical cladding surrounding the optical core, the optical core having a refractive graded- index profile, the optical cladding comprising: an inner layer surrounding said optical core, an intermediate layer, called "depressed trench", surrounding said inner layer, an outer layer surrounding said depressed trench and having a constant refractive index, said depressed trench having a width W and a negative refractive index difference Δn_t with respect to the outer layer, and being designed so as to satisfy the following inequality: $|0.585677 - 114.681 \times S + 13.7287 \times S^2 + 18.7343 \times S \times W - 4.61112 \times S \times \Delta n_t.10^3 - 0.913789 \times W \times \Delta n_t.10^3| + 2 \times W \times \Delta n_t.10^3 < -30$ wherein: S is the width of the inner cladding, which is comprised between 0.6 μm and 1.6 μm; Δn_t is comprised between -11.10^{-3} and -4.10^{-3}; $W \times \Delta n_t.10^3$ is lower than -25 μm.

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Bend-insensitive multimode optical fiber with reduced impact of leaky modes

1. FIELD OF THE INVENTION

The invention relates to fiber optic transmission, and, more specifically, to a bend-insensitive multimode optical fiber having a reduced number of leaky modes.

2. TECHNOLOGICAL 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_c, is greater than the one of the cladding, n_g. 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 Δn between the refractive index at radius r and the refractive index of the optical cladding 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 are propagated simultaneously along the optical fiber, whereas in a single-mode fiber, the higher order modes are cut-off or highly attenuated.

Multimode fibers are commonly used for short-distance applications requiring a high bandwidth, such as local area networks (LANs) and multi-dwelling units (MDUs), more generally known as in-building networks. The core of a multimode fiber typically has a diameter of 50 µm, or 62,5 µm and an alpha refractive graded-index profile. In such applications, the conventional optical fibers can be subjected to unintended bending, which can cause inherent losses and thus modify the mode power distribution and the bandwidth thereof.

The key parameters that ensure good performances of multimode fibers in multi-gigabit Ethernet communications are the bend-loss resistance and the bandwidth.

A known solution to improve bend-loss resistance of multimode fibers consists in adding a depressed-index portion between the graded-index core and the cladding. This depressed-index portion, usually called a depressed trench, has a negative refractive index difference with respect to the optical fiber cladding, and its position and size are designed so as to avoid degradation of the bandwidth.

However, while the presence of a depressed trench improves the bend-loss resistance of the guided optical modes, it also leads to additional parasitical modes, called "leaky modes", to co-propagate with the guided optical modes. Optical rays being partially reflecting at the depressed trench interface, the leaky modes exhibit additional losses (commonly called "leakage losses") compared to the guided optical modes coming from the refractive index profile itself.

The leaky modes are also present within a conventional multimode fiber, i.e. a multimode fiber having no bend-loss resistance means, but they are nearly inexistent in practice, because the level of their leakage losses is extremely high. On the other hand, with a known trench-assisted design of optical fiber, the leakage losses of the leaky modes are so reduced that the leaky modes propagate over several meters and even more, that is critical for compatibility with a conventional multimode fiber. Under OFL (OverFilled Launch) conditions, it was indeed found that the emergence of leaky modes disturbs the characterization measurements, the core size (a) and numerical aperture (NA) measurements being in particular overestimated. This is problematic because the interconnection between fibers requires tight tolerances.

It would be therefore efficient to provide a multimode optical fiber having a limited impact of the leaky modes on the optical characteristics (like the core size and numerical aperture) and still providing a bend-loss resistance, while allowing a broad modal bandwidth.

The patent documents US 2009/0154888, US 2008/0166094, JP 2006/47719, US 2011/0123161, US 2010/0067858, for examples, relate to a graded index optical fiber having a depressed trench within the cladding for reducing bending losses. However, none of these documents discloses a solution to overcome the problem of impact of the leaky modes on the optical characteristics.

The patent document US 2011/058781 also relates to a trench-assisted multimode optical fiber. This document proposes to enhance the bend-loss resistance of the optical fiber by defining the volume of the depressed trench as being comprised between -40 μm and -30 μm. This invention gives a rule that limits the deleterious effect of the leaky modes on the numerical aperture (i.e. on the divergence of light spot output the optical fiber) but does not provide any solution for minimizing the impact on other optical characteristics, like the optical core size for instance. Indeed, the leaky mode leads to an artificial core size enlargement during characterization measurements (the core looks larger than it actually is). Thus, this known solution is not optimal.

3. GOALS OF THE INVENTION

The invention, in at least one embodiment, is aimed especially at overcoming these different drawbacks of the prior art.

More specifically, a goal of at least one embodiment of the invention is to provide a multimode optical fiber that has a limited impact of the leaky modes on the optical characteristics, while providing a high bend-loss resistance and a broad modal bandwidth for multimode transmission.

Another goal of at least one embodiment is to provide a multimode optical fiber that assures a trade-off between the leakage losses and bending losses which is better than the one of prior art optical fibers.

Another goal of at least one embodiment is to provide a multimode optical fiber that is simple to manufacture and costs little.

4. SUMMARY OF THE INVENTION

In one particular embodiment of the invention, it is proposed a multimode optical fiber comprising an optical core and an optical cladding surrounding the optical core, the optical core having a refractive graded-index profile, the optical cladding comprising:

- an inner layer surrounding said optical core,
- an intermediate layer, called “depressed trench”, surrounding said inner layer,
- an outer layer surrounding said depressed trench and having a constant refractive index,

said depressed trench having a width W and a negative refractive index difference Δn_t with respect to the outer layer.

The depressed trench according to the invention is arranged so as to satisfy the following inequality:

$$\left|0.585677 - 114.681 \times S + 13.7287 \times S^2 + 18.7343 \times S \times W - 4.61112 \times S \times \Delta n_t .10^3 - 0.913789 \times W \times \Delta n_t .10^3\right| + 2 \times W \times \Delta n_t .10^3 < -30$$

wherein:

S is the width of the inner cladding, which is comprised between 0.6 μm and 1.6 μm;

Δn_t is comprised between -11.10^{-3} and -4.10^{-3};

$W \times \Delta n_t . 10^3$ is lower than -25 μm.

The general principle is to propose a multimode optical fiber comprising a depressed trench within the optical cladding with an index profile optimized for limiting the impact of the leaky modes on the optical characteristics, while having a high bend-loss resistance. To that end, the values of the inner cladding width S, of the trench width W and the trench index difference Δn_t (also called "trench depth") shall be adequately chosen to satisfy both the inequality and conditions described above.

First of all, in order to limit the impact of leaky modes, the inner cladding width S, the trench width W and the trench depth Δn_t shall satisfy said inequality: it corresponds to an acceptance criterion representative to the impact level of the leaky modes on optical characteristics of the optical fiber. Then, the condition on the inner cladding width S is used to enable the multimode optical fiber to have a high modal bandwidth achievement. The condition on the trench parameter Δn_t is used for large scale production and implementation of optical fibers. Finally, the condition on the product $W \times \Delta n_t . 10^3$ is used to have bending losses as low as possible.

The astute implementation of such depressed trench-assisted optical fiber leads to a trade-off between negative effect of leaky modes and bending losses which is better than the one of prior art optical fibers, while keeping a broad modal bandwidth.

Reducing number of leaky modes propagating within the optical fiber means reducing disturbances in characterization measurements of the multimode optical fibers. The result is in particular a more accurate estimation of measurements of optical core size relative to prior art optical fibers (for which the optical core size are generally overestimated). The trench-assisted multimode fiber according to the invention therefore guarantees a better compatibility with the conventional multimode fibers (free of depressed trench).

In addition, an optical fiber according to the invention is simple to manufacture and costs little, since all that is needed is to adapt doping of the different parts of the optical cladding as a function of the refractive index profile desired for the depressed trench.

Advantageously, the width S of the inner layer is comprised between 0.8 μm and 1.2 μm.

This range of values provides the multimode optical fiber with a high modal bandwidth, essential for short-distance applications.

According to one advantageous characteristic, the negative refractive index difference with respect to the outer layer is comprised between -8.10^{-3} and -4.10^{-3}.

This range of values leads to further reduce bending losses. This is for best trade-off between bend resistance improvement and leaky mode resistance.

In an exemplary embodiment, the inner layer has a constant refractive index substantially equal to the refractive index of the outer layer.

In an alternative exemplary embodiment, which is more advantageous, the inner layer has a refractive index difference with respect to the outer layer which is comprised between about -0.40x10^{-3} and 2.00x10^{-3}, and more precisely between about -0.27x10^{-3} and 1.19x10^{-3}, and even more precisely between -0.10x10^{-3} and 0.60x10^{-3}.

This allows higher bandwidth multimode optical fibers.

Advantageously, the optical core's graded-index profile is an alpha graded-index profile, which can be defined as follow:

$$n(r) = n_0 \cdot \sqrt{1 - 2 \cdot \Delta \cdot \left(\frac{r}{a}\right)^{\alpha}} \quad for\ r < a$$

where:

a is the radius of the optical core;

n_0 is the maximal refractive index of the optical core (which generally corresponds to the index value of the center of the optical core, i.e. for r = 0);

$1.9 \leq \alpha \leq 2.2$, α being a non-dimensional parameter that defines the graded-index profile shape of the optical core;

$\Delta = \frac{n_0^2 - n_1^2}{2n_0^2}$, Δ being the normalized refractive index difference and n_1 the minimal refractive index value of the optical core (which generally corresponds to the index value of the outer cladding).

The alpha refractive index profile of the optical core allows reducing intermodal dispersion. The parameter alpha (α) is chosen so as to provide the largest bandwidth at the target operating wavelength, such as 850 nm or 1300 nm for example.

According to one advantageous characteristic, the optical core has a maximum refractive index difference Δn_0 with respect to the outer layer comprised between about 11×10^{-3} and 18×10^{-3}, more precisely between about 13×10^{-3} and 16×10^{-3}.

Advantageously, the outer end of said depressed trench is separated from the center of the optical fiber at a radius r_t lower than 32 μm, and more precisely lower than 30 μm.

Preferentially, the multimode optical fiber has a numerical aperture comprised between 0.185 and 0.215 and the optical core has a radius a comprised between about 22 μm and 27 μm. Numerical aperture, hereafter called NA, is a dimensionless number that characterizes the range of angles over which the optical fiber can accept or emit light spot. It can be defined by the following equation: $NA = \sqrt{n_0^2 - n_1^2} = n_0 \cdot \sqrt{2\Delta}$

In another embodiment, the invention pertains to an optical system comprising at least one multimode optical fiber described here above in any of its different embodiments. This multimode optical system may be an optical home network, such as a local area network (LAN) and or a multi-dwelling unit (MDU) for example.

5. LIST OF FIGURES

Other features and advantages of embodiments of the invention 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 an optical fiber according to one embodiment of the invention;
- Figure 2 shows a comparison between the depressed-assisted optical fiber of the invention and depressed-assisted optical fiber of prior art described above with reference to technological background, computed according to a linear model in accordance with the invention;
- Figure 3 graphically depicts bending sensitivity of optical fibers in accordance with the invention measured at a wavelength of 850 nm under launching

conditions defined in the standard IEC 60793-1-47, as a function of the trench volume of these optical fibers.

6. DETAILED DESCRIPTION

The general principle of the invention is to propose a multimode optical fiber that comprises a trench-assisted design allowing to limit the negative contribution of the leaky modes on the optical characteristics, in particular (but not exclusively) on the optical core size, while providing bend resistance and high modal bandwidth achievement.

Figure 1 depicts the refractive index profile n(r) of an optical fiber according to one embodiment of the invention. It describes the relationship between the refractive index value n and the distance r from the center of the optical fiber.

The distance r with respect to the center of the optical fiber is shown on x-axis and the difference n(r) - n_1 between the refractive index at radius r and the refractive index of the outer cladding is shown on y-axis.

The fiber of the invention is a multimode optical fiber having an optical core ($0 < r < a$) and an optical cladding ($a \leq r$) surrounding the optical core.

The optical cladding especially comprises, from the center of the optical fiber to the periphery: an inner layer (hereafter called “inner cladding”) surrounding the optical core, an intermediate layer (hereafter called “depressed trench”) surrounding the inner cladding, an outer layer (hereafter called “outer cladding”) surrounding the depressed trench.

The inner cladding directly surrounds the optical core. The end of the inner cladding is located at a radial distance r_c from the center of the optical fiber. It further has a refractive index difference substantially equal to 0 with respect to the outer cladding, since it has a constant refractive index (n_3) which is substantially equal to the one of the outer cladding (n_1) such as: $n_1 = n_0 \cdot \sqrt{1 - 2 \cdot \Delta}$.

The depressed trench directly surrounds the inner cladding. It is located between the inner cladding and the outer cladding at a radial distance between r_c and r_t from the center of the optical fiber. The depressed trench is characterized by three main parameters:

- a trench depth Δn_t that corresponds to the negative refractive index difference with respect to the outer cladding (n_1);
- a trench width W that corresponds to the difference r_t - r_c (expressed in micrometer); and
- a space S separating the beginning of the depressed trench from the end of the optical core, i.e. the difference r_c - a (expressed in micrometer).

According to the invention, these trench parameters Δn_t, W, S are tuned so that they satisfy the following inequality:

$$\left|0.585677-114.681\times S+13.7287\times S^2+18.7343\times S\times W-4.61112\times S\times \Delta n_t.10^3-0.913789\times W\times \Delta n_t.10^3\right|$$
$$+2\times W\times \Delta n_t.10^3<-30$$

The inventors discovered that the left member of this inequality corresponds to an acceptance criterion representative to the impact level of the leaky modes on optical characteristics of the optical fiber. This acceptance criterion has been obtained through a generalized linear model based upon a set of data resulting from a simulation of optical core size after 2 meters of samples of trench-assisted multimode optical fibers and for which refractive index profiles exhibit various values of parameters S, W and Δn_t as summarized in the Table 1 below.

The left member of the above inequality is called hereafter as “acceptance criterion”.

In the context of experimentation carried out on multimode optical fibers, the inventors unexpectedly discovered that the bigger the depressed trench is, the greater the number of leaky modes propagate within the optical fiber, and so the greater the overestimation of the core size measurement is. Based on this principle, depressed trench-assisted optical fibers have been simulated with various values of parameters S, W and Δn_t in order to establish a link between these parameters allowing to optimize the trade-off between bend resistance and impact of leaky modes inherent to the trench assistance concept.

According to an particular embodiment, these trench parameters Δn_t, W, S are further tuned so that they further satisfy the following conditions:

- S is comprised between 0.6 μm and 1.6 μm;
- Δn_t is comprised between -11.10^{-3} and -4.10^{-3};

- the product $W \times \Delta n_t .10^3$ (hereafter called "trench volume") is lower than -25 μm.

Table 1

S (μm)	*W (μm)*	*Δnt (expressed in 10^{-3})*	*Over-estimation (μm)*	*W×Δn$_t$×10^3 (μm)*	*Acceptance criterion*
0,89192	2,6	-9,7851	0,4	-25	-35
0,73795	2,5	-10,2382	0,3	-26	-35
0,68943	2,6	-10,3826	0,4	-27	-35
0,64589	2,6	-10,5123	0,4	-27	-35
0,60716	2,6	-10,6276	0,4	-28	-35
0,57308	2,6	-10,729	0,5	-28	-35
0,54353	2,7	-10,817	0,5	-29	-35
0,51838	2,7	-10,8919	0,5	-29	-35
0,49756	2,7	-10,9539	0,5	-30	-35
0,62061	2,9	-10,4238	0,5	-30	-35
0,50115	3,3	-9,0589	0,6	-30	-34
0,20499	3,6	-8,2694	0,6	-30	-33
0,48982	3,8	-8,0059	0,6	-30	-32
0,95182	3,0	-10,2323	0,7	-30	-31
0,67222	3,9	-7,82	0,8	-30	-30
0,74906	3,9	-7,7189	0,8	-30	-29

From this table, it should be noticed that the variation in measurements of the optical core size (called "overestimation" in the table) for an optical fiber of the invention subject to the OFL conditions does not exceed 0.8 μm. Generally speaking, to characterize a multimode optical fiber under OFL conditions, the optical fiber is subject to a spot of a light source coupled to thereon to equally excite all the guided and leaky modes. The near field pattern of the spot is then observed at the output of the optical fiber and post-processed to assess the optical core size. We observe here that, when values of parameters Δn_t, W, S are chosen so as to meet the acceptance criterion (i.e. lower than -30), the impact of leaky modes on the near field pattern is significantly reduced, thereby making the overestimation of optical core size measurements negligible (i.e. lower than 1.0 μm). Therefore, compared with the trench-assisted-optical fibers of prior art for which the core size overestimation usually tend to be higher than 1.0 μm, those of the invention lead to much more accurate characterisation measurements.

In order to keep a high bend-loss resistance at 5 mm bend radius, the depressed trench according to the invention is designed to have the trench volume ($W \times \Delta n_t .10^3$) lower than -25 μm. Indeed, as will be discussed more thoroughly below in relation with

Figure 3, simulations showed that the bending losses, as well as number of leaky modes, depend mainly on the trench volume of optical fiber.

The parameter S is chosen to allow tuning the modal bandwidth of the multimode optical fiber: S is comprised between 0.6 µm and 1.6 µm.

The trench depth Δn_t is comprised between -11.10^{-3} and -4.10^{-3}, and more preferably between -8.10^{-3} and -4.10^{-3}. This value range allows large scale production and implementation of optical fibers.

By choosing appropriate values of parameters Δn_t, W, S while complying with the acceptance criterion, the invention thus offers a trench-assisted design that allows high bend-losses resistance, in addition to a reduced number of leaky modes.

As a strictly illustrative example, the optical core radius a is about 25 µm and the parameter α of the optical core's index profile is about 2. The optical core has a maximum refractive index difference Δn_0 with respect to the outer layer of about 14.10^{-3} and a normalized refractive index difference Δ of about 1. The end of the inner cladding is located at a radial distance r_c substantially equal to 27.5 µm from the center of the optical fiber. The depressed trench is located between the inner cladding and the outer cladding at a radial distance between r_c and r_t substantially equal to 31.5 µm from the center of the optical fiber. Δn_t is substantially equal to -5.5×10^{-3}, S substantially equal to 1.5 µm and W substantially equal to 5 µm, representing a trench volume $W \times \Delta n_t .10^3$ of -22 µm. The trench's outer end is separated from the optical fiber's center of a radius r_t of about 32 μm and the trench's inner end is separated from the optical fiber's center of a radius r_c of about 27 μm.

In the particular embodiment illustrated in Figure 1, the inner cladding has a standard constant refractive index that is substantially equal to the one of the outer cladding ($n_1 = n_0 \cdot \sqrt{1 - 2 \cdot \Delta}$). One might also envisage, in an alternative embodiment of the invention, that the inner cladding has a refractive index difference with respect to the outer cladding which can be comprised between approximately $-0.4\text{x}10^{-3}$ and $2.0\text{x}10^{-3}$. This refractive index difference, which is either negative or positive with respect to outer cladding, can be obtained by doping the inner cladding properly during manufacturing process. As an illustrative example, a positive refractive index difference of $0.5\text{x}10^{-3}$ allows guarantying a broad modal bandwidth of the multimode fiber optical.

The advantages of the invention will be more evident by comparing optical fibers of the prior art with an exemplary optical fiber according to the invention.

The graph of **Figure 2** depicts the depressed trench volume of trench-assisted optical fibers of prior art and of trench-assisted optical fibers of the invention as a function of the acceptance criterion of the invention (for which the principle is detailed above in relation with Figure 1). The y-axis depicts values of the trench volume $W \times \Delta n_t .10^3$ from the table 1 illustrated above and the x-axis depicts different values of the acceptance criterion.

By comparing the acceptance criterion applied both to the trench-assisted optical fibers of prior art and optical fibers of the invention, the graph of Figure 2 shows the quality of the model that leads to the establishment of the acceptance criterion according to the invention. In particular, it can be observed that none of the assisted-trench optical fibers of prior art does meet the acceptance criterion of the invention. Contrary to the invention, none of the optical fibers of prior art thereby offers a trench-assisted design that allows high bend-losses resistance, in addition to a reduced number of leaky modes.

Figure 3 graphically depicts bending losses of optical fibers in accordance with the invention measured for 2 turns with 7.5 mm bend radius and at a wavelength of 850 nm, as a function of the trench volume of these optical fibers.

The left-hand y-axis depicts macro-bending losses or macro-bending sensitivity (expressed in dB) of a set of optical fibers measured at 850 nm under launching conditions defined in the standard IEC60793-1-47. The term *"BL 2tr 7.5mm 850nm"* refers to launching conditions under which measurements were made: optical fibers has been subject to a wavelength of 850 nm for 2 turns around a 7.5 mm bend radius mandrel. The trench volume $W \times \Delta n_t .10^3$ (expressed in µm) is depicted on the graph x-axis. A right-hand y-axis has further been added for depicting the relationship between the trench volume $W \times \Delta n_t .10^3$ and the leaky mode contribution (expressed in %) measured these optical fibers.

It can be seen that the trench-assisted multimode optical fibers according to the invention exhibit bending losses lower than 0.4 dB while having a leaky mode contribution relatively low, lower than 0.03%. The shaded area particularly indicates the optical fibers that do not meet the requirements of trench volume ($W \times \Delta n_t .10^3 \leq -25 \mu m$).

Therefore, this demonstrates that the multimode optical fibers in accordance with the invention offer an improved trade-off between bend resistance and leaky mode resistance.

Finally, in another embodiment, the invention pertains to an optical system comprising at least one portion of a multimode optical fiber described here above in any of its different embodiments. This multimode optical system may be an optical home network, such as a local area network (LAN) and or a multi-dwelling unit (MDU) for example.

CLAIMS

1. Multimode optical fiber comprising an optical core and an optical cladding surrounding the optical core, the optical core having a refractive graded-index profile, the optical cladding comprising:

- an inner layer surrounding said optical core,
- an intermediate layer, called "depressed trench", surrounding said inner layer,
- an outer layer surrounding said depressed trench and having a constant refractive index,

said depressed trench having a width W and a negative refractive index difference Δn_t with respect to the outer layer,

characterized in that said depressed trench is arranged so as to satisfy the following inequality:

$$\left|0.585677 - 114.681 \times S + 13.7287 \times S^2 + 18.7343 \times S \times W - 4.61112 \times S \times \Delta n_t .10^3 - 0.913789 \times W \times \Delta n_t .10^3\right| + 2 \times W \times \Delta n_t .10^3 < -30$$

wherein:

S is the width of the inner cladding, which is comprised between 0.6 μm and 1.6 μm;

Δn_t is comprised between -11.10^{-3} and -4.10^{-3};

$W \times \Delta n_t .10^3$ is lower than -25 μm.

2. Multimode optical fiber according to claim 1, wherein the width S of the inner layer is comprised between 0.8 μm and 1.2 μm.

3. Multimode optical fiber according to any one of claims 1 or 2, wherein the negative refractive index difference Δn_t with respect to the outer layer is comprised between -8.10^{-3} and -4.10^{-3}.

4. Multimode optical fiber according to any one of claims 1 to 3, wherein the inner layer has a constant refractive index substantially equal to the refractive index of the outer layer.

5. Multimode optical fiber according to any one of claims 1 to 3, wherein the inner layer has a refractive index difference Δn_t with respect to the outer layer which is comprised between about -0.40×10^{-3} and 2.00×10^{-3}, and more precisely between about -0.20×10^{-3} and 1.10×10^{-3}, and even more precisely between about -0.10×10^{-3} and 0.60×10^{-3}.

6. Multimode optical fiber according to any one of claims 1 to 5, wherein the optical core's graded-index profile is an alpha graded-index profile with an alpha parameter comprised between 1.9 and 2.1.

7. Multimode optical fiber according to any one of claims 1 to 6, wherein the optical core has a maximum refractive index difference Δn_0 with respect to the outer layer comprised between about 11×10^{-3} and 18×10^{-3}, more precisely between about 13×10^{-3} and 16×10^{-3}.

8. Multimode optical fiber according to any one of claims 1 to 7, wherein the outer end of said depressed trench is separated from the center of the optical fiber of a radius r_t lower than 32 μm, and more precisely lower than 30 μm.

9. Multimode optical fiber according to any one of claims 1 to 8, having a numerical aperture of between 0.185 and 0.215.

10. Multimode optical fiber according to any one of claims 1 to 9, wherein the optical core has a radius *a*, from the center of the optical fiber, comprised between about 22 μm and 27 μm.

11. Multimode optical system comprising at least one optical fiber according to any one of claims 1 to 10.

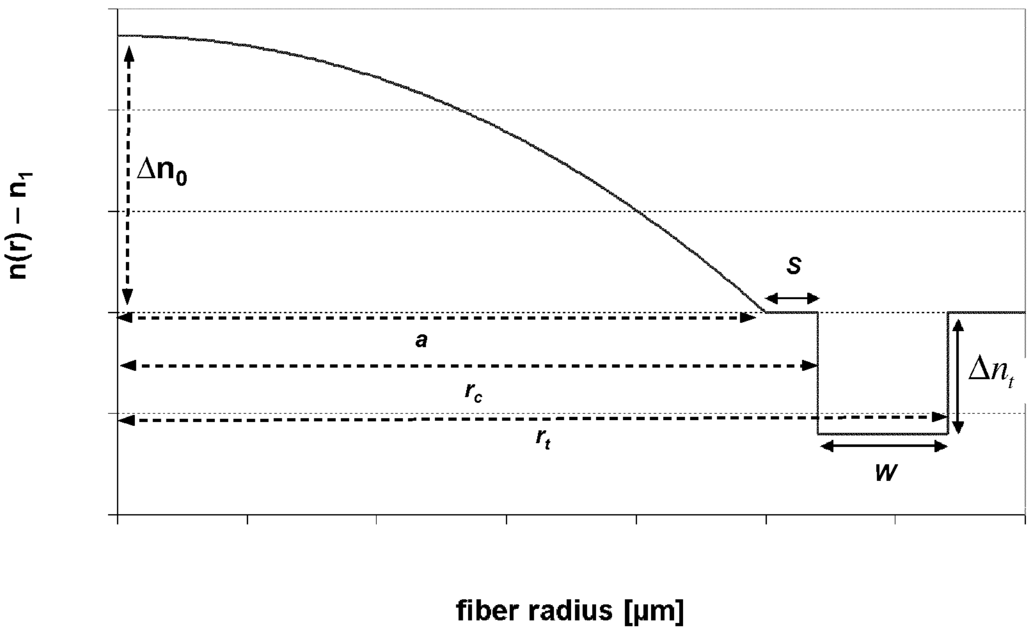

Figure 1

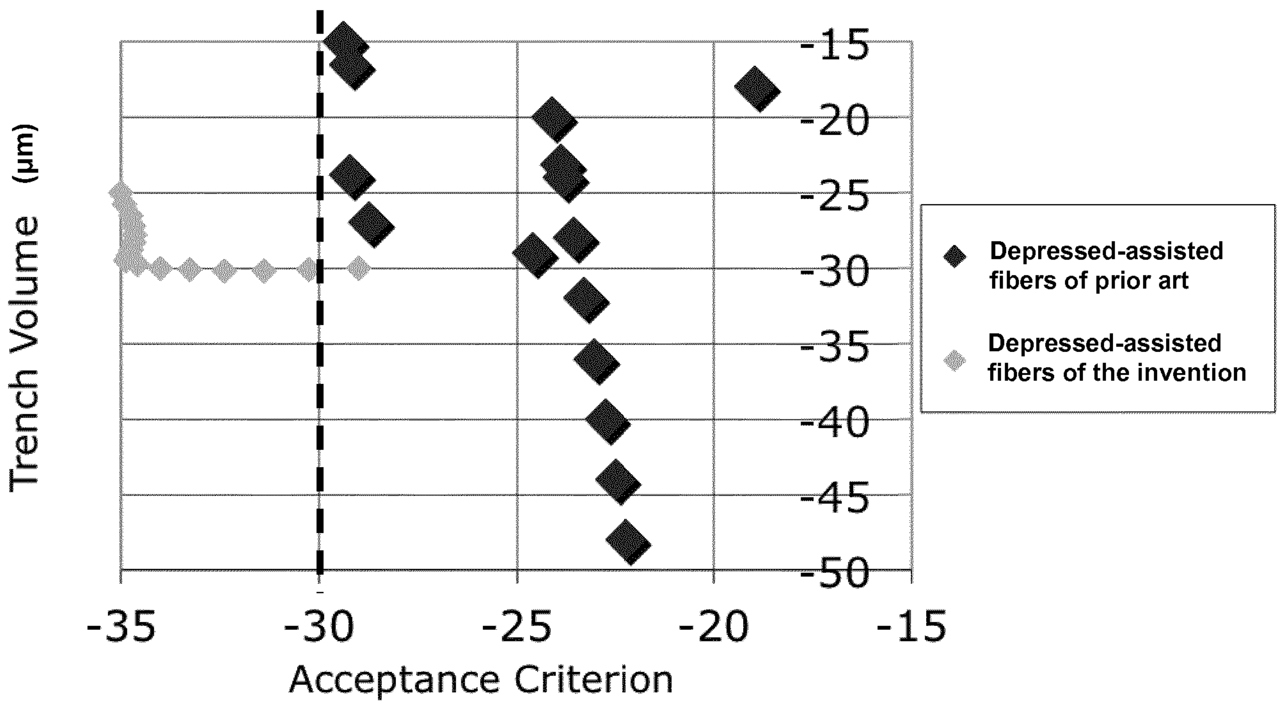

Figure 2

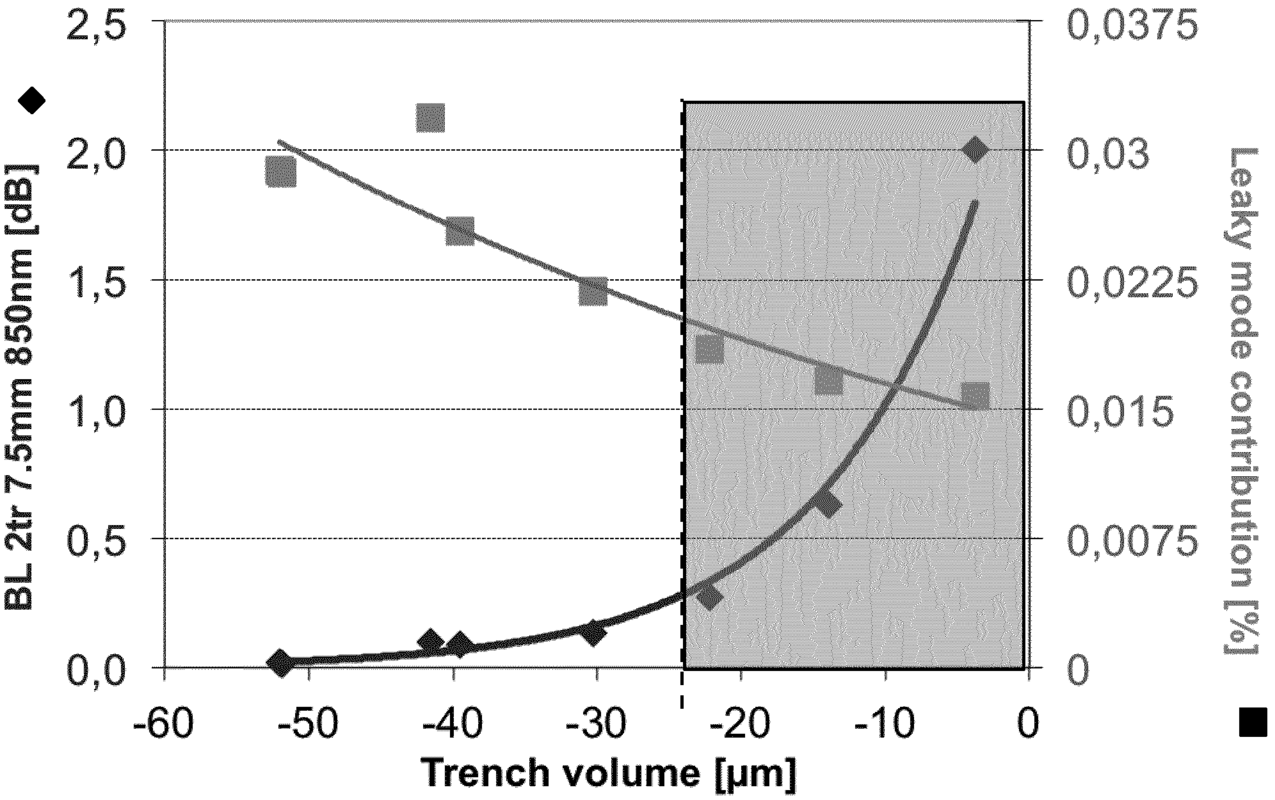
2,5
2,0
1,5
1,0
0,5
0,0
BL 2tr 7.5mm 850nm [dB]
0,0375
0,03
0,0225
0,015
0,0075
0
Leaky mode contribution [%]
-60
-50
-40
-30
-20
-10
0
Trench volume [µm]

Figure 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/063417

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2013/028564 A1 (MOLIN DENIS [FR] ET AL) 31 January 2013 (2013-01-31) claims 7, 8, 11 paragraph [0062]	1-8,10, 11
X	EP 2 299 302 A1 (DRAKA COMTEQ BV [NL]) 23 March 2011 (2011-03-23) claims 3, 5, 6, 9 figure 8 paragraph [0020]	1,3,4, 7-9,11

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

☒ See patent family annex.

* Special categories of cited documents :

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 January 2014	06/02/2014

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Orignac, Xavier

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2013/063417

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013028564 A1	31-01-2013	NONE	
EP 2299302 A1	23-03-2011	CN 102023333 A	20-04-2011
		EP 2299302 A1	23-03-2011
		FR 2949870 A1	11-03-2011
		JP 2011059687 A	24-03-2011
		US 2011058781 A1	10-03-2011