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Recent advances in optical telecommunications / Avancées récentes en télécommunications optiques

Latest advances in optical fibers

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Abstract

Optical fibers can now be encountered anywhere in a telecommunication network. In that field, one of the major changes that occurred, at the turn of the Century, is the growing interest in Fiber-to-the-Home (FTTH) architectures, that is, optical fibers replacing copper in access networks to directly connect subscribers. This gave birth to a new category of single mode fibers referred to as bend-insensitive fibers, which has represented one of the major development focus of optical fiber manufacturers for the last 5 years. In parallel, key evolutions also took place in data communications with the decision to create, at the end of this decade, the next generation Ethernet hierarchy for equipment interfaces at rates of 40 and 100 Gb/s. This is driving recent research on fibers to be used to transport such high-rate signals between these equipments. ***To cite this article: L.-A. de Montmorillon et al., C. R. Physique 9 (2008).***

Résumé

Avancées les plus récentes en fibres optiques. Les fibres optiques interviennent désormais partout dans les réseaux de télécommunication. L'un des changements le plus notable dans ce domaine est l'intérêt croissant depuis le début du siècle pour amener la fibre jusque la maison (FTTH), soit un remplacement du cuivre par la fibre dans les réseaux d'accès afin que l'abonné soit littéralement connecté optiquement. Cela a donné naissance à une nouvelle catégorie de fibres optiques monomodes, les fibres dites insensibles aux courbures, et a représenté l'un des axes principaux de développement des fabricants de fibres optiques depuis 5 ans. Parallèlement, des évolutions clés ont également eu lieu dans le domaine des transmissions de données avec la décision de créer, à la fin de cette décennie, une nouvelle génération de hiérarchie Ethernet permettant d'interfacer des équipements à des débits de 40 et 100 Gb/s. Cela a motivé des travaux récents sur les fibres optiques nécessaires pour véhiculer l'information entre ces équipements. ***Pour citer cet article : L.-A. de Montmorillon et al., C. R. Physique 9 (2008).***

Keywords: Optical fiber; FTTH; Holey fiber; Multimode fiber; Bend-insensitive fiber

Mots-clés : Fibre optique ; FTTH ; Fibre à trous ; Fibre multimode ; Fibre insensible aux courbures

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1. Introduction

Optical fibers are now widely deployed, covering an impressive array of applications ranging from biomedical, telemedicine, and industrial (automation, sensors, etc.), to space, automotive and, of course, telecommunication (voice, data, television, music, video, etc.), from houses to super-capacity backbone pipes. Optical fiber is the only technology that allows versatility, immunity to external parasitical radiation, and the capacity to transmit unrivaled flows of data.

This article aims at providing an update, with latest advances, to the information that was detailed in [1], which described the history of optical fibers, highlighted the key optical fiber characteristics, reviewed the elements of fiber design for optimized optical transport networks, and depicted the fiber evolutions which occurred in the 1990s.

One of the major changes that occurred in telecommunications at the turn of the Century, is the growing interest in Fiber-to-the-Home (FTTH) architectures, that is, optical fibers replacing copper in access networks to directly connect subscribers. There are different types of fiber depending on the part of the network where they are deployed (single mode fibers of different kinds, multimode fibers of different classes depending on the capacity-reach to be targeted), and the advent of FTTH gave birth to a new category of single mode fibers referred to as bend-insensitive fibers.

In data-communications, key evolutions also took place with the decision to create, at the end of this decade, the next generation Ethernet hierarchy for equipment interfaces at rates of 40 Gb/s and 100 Gb/s [2]. This drives recent research on fibers to be used to transport such higher rates signals between such equipments.

This guided tour into latest optical-fiber progress will be sub-divided into three parts. The first part will be dedicated to the recent developments in optical fiber standards. The second part will depict in more details the revolution of bend-insensitive single mode fibers. At last, the third part will be dedicated to the latest developments in fibers for data communication: high-speed multimode fibers.

2. Evolution of standards for optical fibers

2.1. Recommendation for dispersion-optimized fibers G.655 and G.656

The 1990s have witnessed the massive installation on long-distance networks, thanks to the invention of optical amplification in the late 1980s and the introduction of Dense-Wavelength-Division-Multiplexing (DWDM). To cope with the new optical system requirements, several single-mode fiber types with shifted chromatic dispersion characteristics have been developed, the so-called Non-Zero-Dispersion-Shifted Fiber (NZDSF), standardized as G.655 fibers [1,3]. After 2002, further developments took place to adjust the dispersion properties of such NZDSF to make them suitable for operations in S-, C- and L-bands: this gave birth to ITU-T NZDSF recommendation G.656 [4]. In addition, these NZDSF recommendations G.655 and G.656 have further been revised to refine their chromatic dispersion specifications, for improved system design, as explained below.

The ITU-T recommendation G.655 has first been developed in 1996. It describes a single mode optical fiber with an absolute value of chromatic dispersion greater than some non-zero value throughout the wavelength range from 1530 nm to 1565 nm. This non-zero dispersion value reduces the growth of non-linear effects which are particularly deleterious in DWDM systems, as compared to Dispersion Shifted Fibers (DSF) or G.653 with zero-dispersion value. Such NZDSFs also exhibit lower dispersion values as compared to regular single mode fiber G.652, also known as “standard” single mode fiber (SSMF), further handling parasitical cross non-linear effects between channels but yielding to higher dispersion compensation needs.

The first two versions of G.655 created tables from A to C (G.655.A to G.655.C), which described the chromatic dispersion in wavelength-independent minimum and maximum values, over the wavelength range of 1530 nm to 1565 nm (C-band), as reported in Fig. 1(a).

Since, in reality, the chromatic dispersion of optical fiber is varying with wavelength, system engineers, using various wavelength ranges for WDM transmissions, required a more realistic description of the behavior. In 2006, the third version was approved introducing two new categories – G.655.D and G.655.E – that limit chromatic dispersion by a pair of bounding curves, versus wavelength, for the range of 1460 nm to 1625 nm.

In G.655.D (low dispersion fibers) the chromatic dispersion for wavelengths greater than 1530 nm is positive and of sufficient magnitude to suppress to some extent most non-linear impairments, enabling DWDM applications to be supported over these wavelengths (C- and L-band), see Fig. 1(b). Although the dispersion can change sign at wavelengths

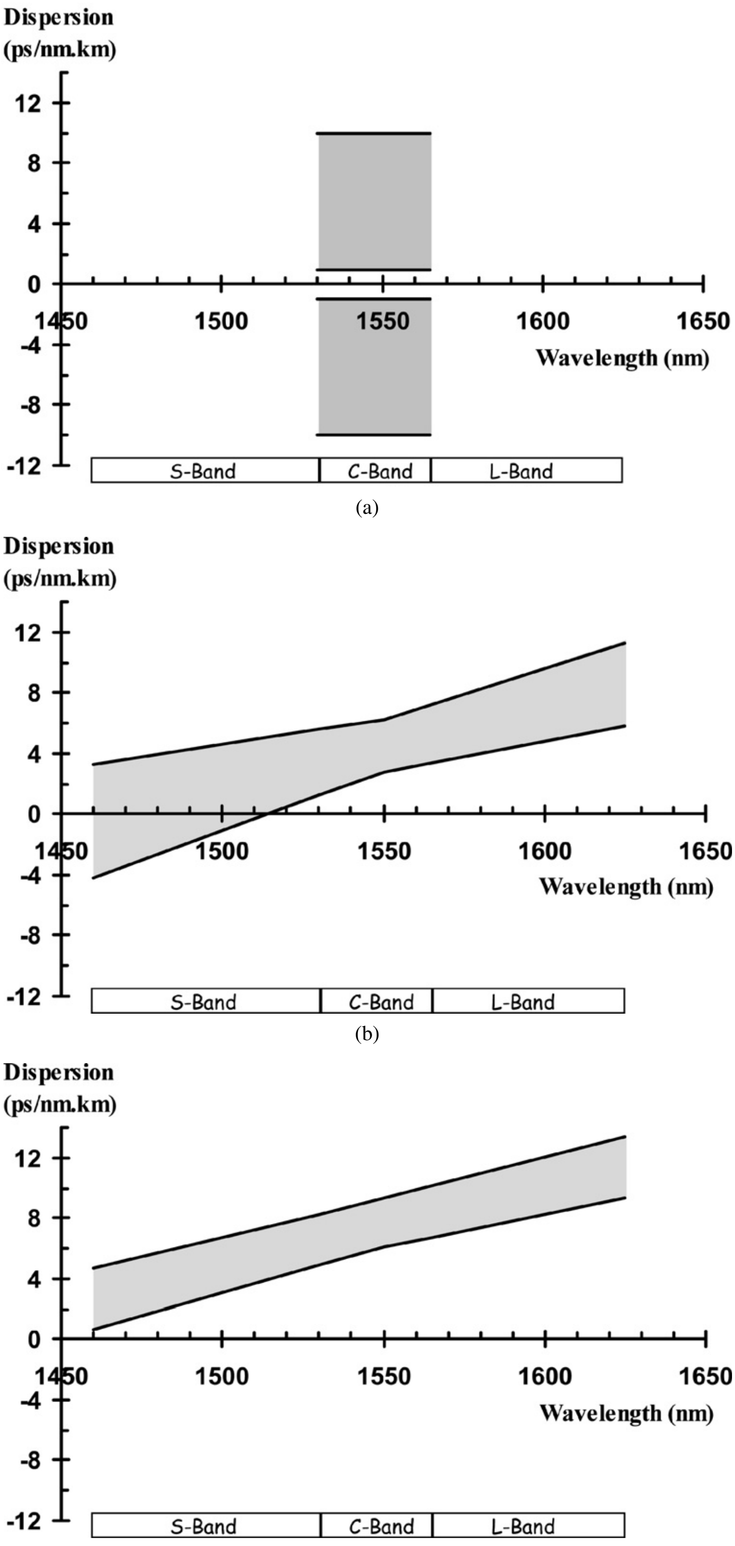

Fig. 1. (a) Chromatic dispersion specification of G.655 NZDSF according to the 2003 edition. (b) Low dispersion G.655.D NZDSF dispersion boundary (2006 edition). (c) Medium dispersion G.655.E NZDSF dispersion boundary (2006 edition).

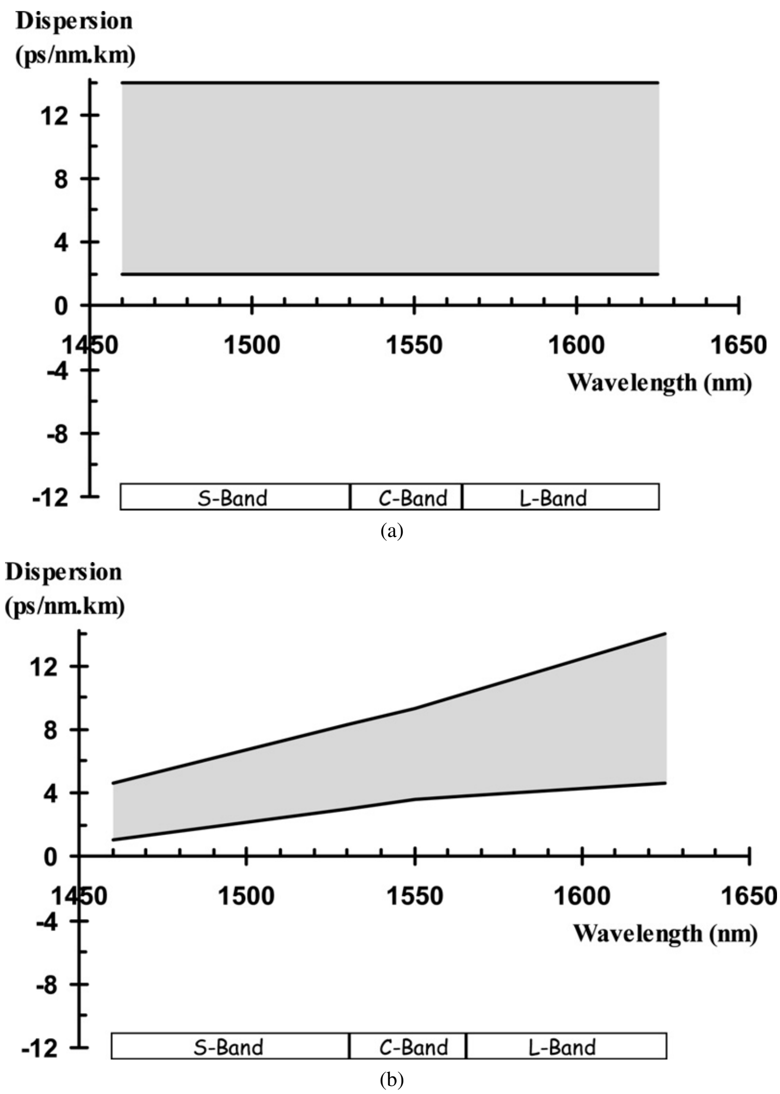

Fig. 2. (a) G.656 NZDSF dispersion boundary (2004 edition). (b) G.656 NZDSF dispersion boundary (2006 edition).

less than 1530 nm, the inclusion of these lower wavelengths is intended to provide information to support coarse wavelength division multiplexing (CWDM) applications which do not have significant non-linear impairments. For G.655.E (medium dispersion fibers), chromatic dispersion is slightly higher than for G.655.D which is of importance for some systems, typically those with the smallest channel spacing. G.655.E fibers show positive and non-zero chromatic dispersion values at all wavelengths above 1460 nm, opening S-, C- and L-band windows for potential DWDM transmissions (see Fig. 1(c)).

In 2004, ITU-T agreed to introduce a new recommendation, G.656, covering NZDSF fibers optimized for wideband optical transport in the S-, C- and L-band (1460 nm to 1625 nm). With a chromatic dispersion greater than some non-zero value throughout the wavelength range of 1460-1625 nm, the growth of non-linear effects, which can be particularly deleterious in DWDM systems, is reduced as compared to some G.655-compliant NZDSF. Originally, in the first edition, the chromatic dispersion was also expressed in minimum and maximum values, independent of the wavelength (Fig. 2(a)). In 2006, this G.656 recommendation was also updated by expressing the chromatic dispersion coefficient requirements as a pair of bounding curves versus wavelength for wavelengths from 1460 nm to 1625 nm (Fig. 2(b)).

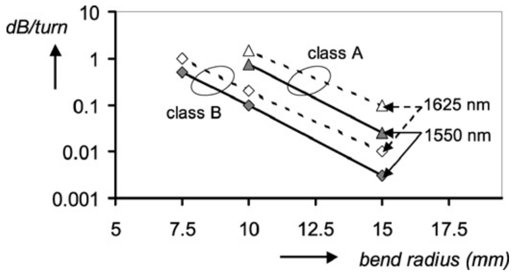

Fig. 3. Bend loss specifications of G.657A and G.657B, at 1550 nm and 1625 nm wavelengths.

Table 1
Main characteristics of G.657A and G.657B fibers.

Attributes	G.657A		G.657B		
MFD 1310 nm					
Nominal range	8.6–9.5 μm		6.3–9.5 μm		
Tolerance	±0.4 μm		±0.4 μm		
Macrobending loss					
Radius (mm)	15	10	15	10	7.5
Number of turns	10	1	10	1	1
Max. at 1550 nm (dB)	0.25	0.75	0.03	0.1	0.5
Max. at 1625 nm (dB)	1.0	1.5	0.1	0.2	1.0
Main transmission attributes (PMD/Chrom. Dispersion)	As per G.652D		TBD		

2.2. New development for FTTH applications: bend-insensitive single-mode fiber (Rec. G.657) and multimode fiber (Rec. G.651.1)

After the collapse of the internet bubble time, the focus of fiber installations moved away from the long-distance networks towards the access networks and more specifically Fiber-to-the-x (FTTx) applications. Starting in Asia (Japan, Korea), then followed by North America and nowadays more and more also Europe, optical fiber roll-outs happened for the last drop. This environment required enhanced robustness property of optical fibers, in order to facilitate easy and cheap installation. Hence, bending insensitive behavior became the prime investigation area of fiber manufacturers.

In 2006, after a very short development time of only two years, a new ITU-T recommendation became available: G.657 [5]. This recommendation identifies two classes: G.657.A shows slightly reduced bending sensitivity compared to already existing G.652.D fibers ("standard" single mode fibers) with full compatibility with this worldwide and most commonly installed fiber type. G.657.B fiber shows further reduced bending sensitivity (see Fig. 3), but this category contains a wider range of different fiber implementations, reason why this category, as a whole, is not G.652.D compliant (Table 1). However, inside this family, some implementations offer full compliance.

In some FTTH applications, in particular for multi-dwelling buildings, it may be advantageous to copy the very successful multimode fiber architecture used in business networks. In combination with an active switch in the basement, such a multi-dwelling building can be installed with a high speed future-proof internal optical network. Especially for this particular section of FTTH applications, ITU-T developed in 2007 the new G.651.1 recommendation for cost-effective use of 1 Gb/s Ethernet systems over link lengths up to 550 m, usually based upon the use of 850 nm transceivers. This recommendation replaces the old G.651, which has been deleted recently.

2.3. High speed multimode fiber (OM3)

In the Datacom world, the demand for higher speeds is impressive. Already soon after the introduction of the IEEE 1 Gigabit Ethernet standard in 1998, the work started for the next higher speed on 10 Gb/s which resulted in the 10 Gigabit Ethernet standard in 2002. Part of the solutions is for longer distances (10 km and 40 km); yet short distance low-cost 10 Gb/s connectivity is needed at many places, like LAN, Data Centers and even Telecom offices, which resulted also in multimode solutions. Especially for this upgrade in Datacom speeds, a new high speed multimode fiber has been developed, often referred to as OM3 fiber (in IEC this fiber is standardized as type A1a.2). This fiber – operated at 850 nm in combination with VCSEL sources – is able to bridge 300 m at 10 Gb/s. More details on multimode fibers will be provided in Part III of this article. At present IEEE is actively working on the next higher speed platform 40 Gb/s and 100 Gb/s.

3. Update on bend insensitive fibers

Macrobend losses of single mode fibers have been optimized for classical telecommunication networks a long time ago. This ended up in the ITU-T recommendations and IEC standards with the current requirement of a maximum added loss of 0.1 dB at 1625 nm for 100 turns with a 30 mm radius [7].

New emerging FTTH telecommunication systems have recently induced much more challenging needs, at the origin of the recent G.657 (A & B) ITU-T recommendations above-mentioned. Indeed, in this harsh environment, lower volume at the storage points is required (with radii down to 15 mm), as well as increased resistance towards incidental bends originating from improper fiber deployment, sharp bend for installation in corners or also, when stapling the cable along a wall.

Several refractive index profile design strategies have been proposed to produce fibers compliant with G.657A and/or G.657B recommendations. For classical step-index single-mode fiber, well-known solution to reduce bending sensitivity consists in decreasing the Mode Field Diameter (MFD) over cutoff wavelength ratio (defined as MAC value) by increasing cut-off wavelength and/or decreasing mode-field diameter [8–10]. However, bending loss levels remain significantly high when applying incidental kinks with radii in the order of 1 to 10 mm. Moreover, there is not much room to decrease the MAC value if fiber is to be kept compatible with the ITU-T G.657 "class A" standard. Indeed, MFD can only be varied within a well-defined range as shown in Table 1. So, step-index profile can be designed to be compliant with G.657A (small core designs) or G.657B (very small core designs), but there are no solutions here to get fibers that are both G.657A&B compliant.

New types of fibers have been proposed to solve this issue. They all exhibit a depressed refractive index area in the cladding layer near the core that enables improved confinement of the light to the core area, whatever the fiber condition. We can distinguish three types of depressed-assisted profiles: solid-trench-assisted, with different options ([11] and [13]), random-void-assisted [12] and hole-assisted [9] step-index structures. While solid-trench-assisted designs are mature and showed industrial compatibility, random-void-assisted, replacing the trench in the cladding by a ring of voids surrounding the fiber core, have demonstrated promising results but have raised questions about splicing, connectorization, performance homogeneity and physical strength. Same applies for the last category, so called hole-assisted designs, which are in the early stages of development and the same major aspects of manufacturing costs, splicing, connectorization and physical strength are being carefully investigated. The next paragraphs will give more details first on the solid glass option, and then the hole assisted option.

3.1. Trench assisted fiber designs

As described above, trench-assisted solutions [14,15] (see Fig. 4) consist of a classical step-index core with a cladding that includes a depressed layer (so-called "trench"). In [15], we showed through careful design analysis of all profile parameters, that it is possible to find an optimized trench design that improves the fundamental mode confinement without reducing its MFD. This is illustrated in Fig. 5: trench impacts on the tail of the optical field when it is sufficiently far from the core, but also impacts on the total shape when it becomes too close to the core. Tailoring the fundamental-mode tail only confines the mode inside the fiber and limits the bending loss without modifying the fundamental mode nature, i.e. its MFD and its chromatic dispersion. So, former trade-off between bend losses and MAC value is improved thanks to this optimized trench-assisted solution.

Fibers fully compatible with G.657A&B recommendations were demonstrated with such a type of structure, which shows improved bending losses together with G.652 standard attributes [11]. Trench also improves microbending sensitivity, which is further improved when low primary coating modulus is used. On the one hand, such reduced microbending sensitivity paves the way for new, smaller and more robust cables for use to and in homes and busi-

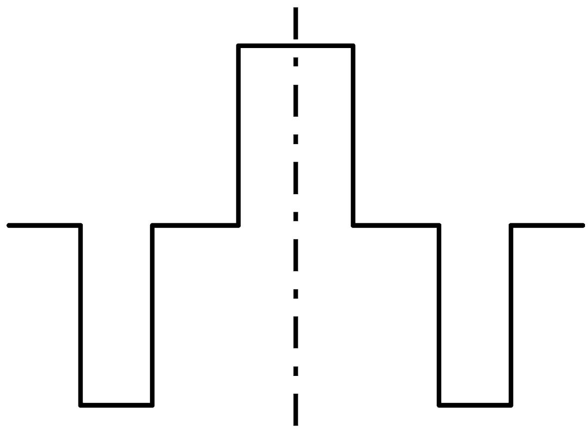

Fig. 4. Schematic trench-assisted profile cross-section.

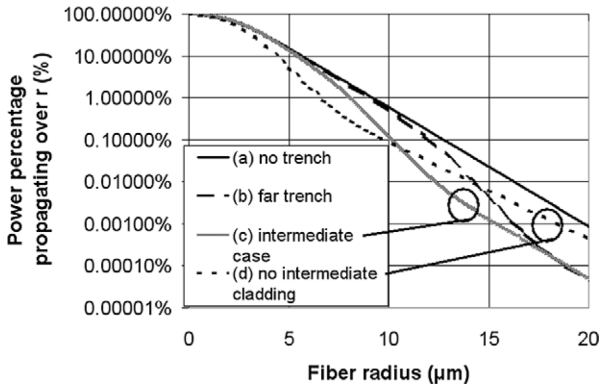

Fig. 5. Computation of optical field for different trench-assisted refractive index profiles.

ness [17]. On the other hand, it yields improved performance at low temperature, e.g. down to −60 °C as reported in [16].

It was also demonstrated that trench-assisted fibers offer improved safety in high power applications ranging from 1360 nm to 1625 nm in case of tight fiber bends [18]. A real danger of degradation indeed exists when the power lost at the bend is absorbed by the coating and the temperature exceeds ∼85 °C. With a launched power of 2.5 W and bend radius of 4 mm, a typical trench assisted fiber exhibits a temperature of 30 °C whereas typical G652 step index fiber reach temperature of ∼150 °C. Trench assisted fiber was measured to withstand 1 W at 1625 nm for bend radius as low as 3 mm whereas the reference G652 step index was limited to a 10 mm radius.

All these results prove that the trench significantly improves the bending performance of the fiber. This improvement is obtained while insuring a full backward compatibility with the former step-index fiber generation. Fusion splicing between the two types of fiber gives equivalent performance as former fusion splicing between two regular step-index fibers [16], when selecting the optimum settings.

At last, the final decisive advantage of “trench” solutions is their compatibility with mature process deposition technologies, such as versatile Plasma Chemical Vapor Deposition (PCVD), thus enabling large-scale production.

3.2. Hole assisted fiber designs

Hole Assisted Fibers (HAF) include a central core, whose refractive index difference is very close to that of standard single mode fiber (SMF), which is surrounded by a small number of air-hole rings (2 at the most) as depicted in Fig. 6. Here, the holes act as a trench with lower index of refraction that allows one to further confine the fundamental mode and thus reduce bending loss.

This type of fiber was first introduced in 2001 [19]. Authors proposed to surround a regular SMF-core by a ring of 6 holes, that would further assist the guiding process. In doing so, guiding would still occur even in case the holes are blocked, which is not the case in all-silica photonic crystal fibers, and which can happen when fusion splicing. Low-bending-loss potential of this structure was recognized as well and the lowest loss ever achieved for a structure with air holes (0.8 dB/km at 1.55 µm) was reported. In this realization, fiber was made using a pure-silica core and a F-doped cladding including the holes. The same authors presented an improved HAF version in [20] with respect to bending performance, while maintaining good spliceability with SMF. Design is more complex, with 2 rings of 6 and 12 holes respectively (same diameter) surrounding a standard GeO_2-doped core. Fiber has final diameter of 80 µm to prevent breaks more efficiently at low bending radius. Loss at 1.55 µm was improved at 0.53 dB/km and further improved at 0.39 dB/km in [21].

Since then, other authors have published on HAF with different design parameters and optical properties. A simple bend-resistant one-ring structure was reported in [22] while structures with 2 rings of holes are described in [23] and [24], with extensive modeling work in [24]. The structure of [24] includes 2 rings of holes with different diameters for the first and second ring, which makes manufacturing process more complex. However, authors underline that 2

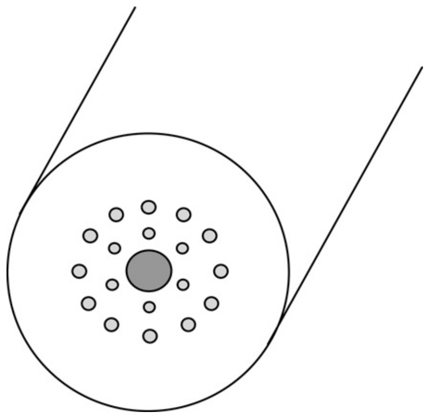

Fig. 6. Cross section of HA-SMF. Centre dark-grey part represents the core, GeO_2 doped. The light-grey disks represent the air holes, embedded in silica.

Table 2
Summary of propagation characteristics for prototype fibers published in the literature.

Ref., year	Loss 1.55 μm	λ_c	Disp. 1.55 μm	λ_0	MFD 1.55 μm	MAC 1.55 μm	Bend. loss $R = 10$ mm 1.55 μm	Bend. loss $R = 7.5$ mm 1.55 μm	Bend. loss $R = 5$ mm 1.55 μm	Splice to SMF
	dB/km	nm	ps/nm/km	nm	μm		dB/m	dB/m	dB/m	dB
[2] – 2003	0.53	1490			6.9	4.63		0.04	0.06	0.13
[3] – 2004	0.39	1280	35.7		6.2	4.84	0.003	∼0.007	0.01	0.2
[4] – 2003							0.001			<0.5
[5] – 2004	0.34	<1310		1300	11.3	>8.63		<0.1 dB/m (1310 nm)		0.2
[6] – 2005	2.3	1100	21.8		9.3	8.45	0.032		0.35	0.08
[7] – 2004	0.273	1240	26.1		8.67	6.99	0.13	0.45	1.97	0.05

rings of holes are necessary to ensure low bending loss for the fundamental mode, and high bending loss (small cut-off wavelength) for the first higher-order mode, which is also claimed in [20].

A slightly different and simpler structure has been proposed in [25]. It includes a GeO_2 doped core surrounded by 2 rings of only 3 holes. However, hole diameter is also different for each ring. A record low loss of 0.27 dB/km at 1.55 μm and very low splice loss of 0.05 dB is reported.

Table 2 summarizes all the main characteristics that have been previously reported. It is clear from this table that very low bending loss values have been reported, but for fibers with very low MAC values. Hence further investigation is needed to fully assess the potential of such structure.

4. Update on multimode fibers

Besides single-mode fibers extensively described in the previous paragraphs, which are used for the telecom environment (long distance, metropolitan, access, FTTx), multimode fibers (MMF) are used in the datacom world (short distance in-building enterprise networks). The large core diameter of such fibers (50 μm or 62.5 μm) offers much more relaxed tolerances in the connectorization between fibers and to sources. Specifically the source to fiber coupling results in cheaper transmitters compared to transmitters for single-mode fibers (by reduced assembly costs), a prerequisite in datacom applications with point-to-point network constructions where (high) costs of a source cannot be shared over multiple users.

The great majority of MMF based datacom systems have been installed in the past for intended bit-rates below 1 Gb/s, using cheap and easy to couple Light Emitting Diodes (LEDs) as sources. The drawback of these sources is their limited modulation bandwidth (<1 Gb/s) and wide spectral width, which – in combination with the fiber chromatic dispersion (wavelength dependent time delays) – may introduce large limitation of the fiber transmission capacity (system bandwidth). The development of cost-effective, high-speed 850 nm Vertical Cavity Surface Emitting

Lasers (VCSELs), showing small spectral width, was the key in achieving higher data speeds. In combination with laser-optimized graded-index multimode fibers (LO-MMF), IEEE standardized 1 Gb/s Ethernet over a distance of 550 meters (1000BASE-SX) in 1998 and even 10 Gb/s Ethernet over a distance of 300 meters (10GBASE-SX) in 2002 for datacom systems in enterprise networks, in particular for backbone connections. These distances cover most of the connections in these networks.

Unlike single-mode fibers, multimode fibers carry more than one mode, traveling along the fiber core with different velocities, resulting in Differential Mode Delays (DMD). This introduces a capacity limitation, called intermodal bandwidth, which also depends on the launch conditions of the multimode fiber. These conditions determine the amount of power carried over the different mode (groups).

Around 2002, together with the development of 10GBASE-SX, a new class of 50 μm core diameter multimode fibers was developed, optimized for laser launch. Such fibers show dramatically improved intermodal bandwidth and are characterized by means of DMD. They are optimized for a very precise core refractive index design, leading to differences in modal delay times below 0.3 ps/m. The popular acronym for such fibers is OM3.

Since the introduction of the OM3 fiber, fiber manufacturers even developed a higher grade of LO-MMF, the currently still unofficial OM4 fiber. Such a fiber could offer longer 10GBASE-SX distances, e.g. up to 550 meters, or additional margins e.g. for use in Data centers where often more connectors are used. Proposals for standardization of this OM4 LO-MMF are currently underway.

Recently, IEEE 802.3 has started new discussions about the next generation Ethernet; a new task force (IEEE P802.3ba) was approved in December 2007 to prepare two system speeds: 40 Gb/s Ethernet (40 GbE) for the server environment and 100 Gb/s Ethernet (100 GbE) for core network and data centre applications, both to be completed by 2010. Again, MMF versions are foreseen using OM3 fibers to distances up to at least 100 meters. Two primary solutions for MMF are under investigation: the parallel solution (4 or 10 fibers parallel, e.g. in ribbon) and Coarse Wavelength Division Multiplexing (CWDM), in both cases with 10 Gb/s per channel. A combination of both may also be used.

5. Conclusion

The world is definitely turning digital. Aside regular telephone and web browsing, content-rich services such as music, images and video have now a tremendous impact on communications, hence telecommunication infrastructures. To back such accelerated capacity demand in worldwide exchanges, data rates kept on increasing and optical fiber, which is the most versatile media that can be used to convey information, is conquering more and more footprint in operators' networks. Optical fiber can now be encountered anywhere in a network, in submarine links, long distance terrestrial networks, metropolitan and access loops, Fiber-to-the-Home drop architectures and even inside building and houses.

There are different types of fiber depending on the part of the network where it is deployed, having conducted to different kind of fiber standards, single mode and multimode, with several sub-categories to cover all specific needs associated to given topologies and environments. Several standards have been developed for single mode, G.655 and G.656 families, to serve the variety of infrastructure configurations. For multimode, with bit rate increasing and ever faster Ethernet interfaces being standardized (1 Gb/s then 10 Gb/s and tomorrow 40 Gb/s and 100 Gb/s), new fiber recommendations were also issued (OM3) to clarify launch conditions and bandwidth requirements to transport such rates on the necessary distances to cover in-building needs.

Another remarkable change is the fast-paced growth of Fiber-to-the-Home roll-out, which begun at the turn of the Century, and which is heavily sustaining the demand for single mode fiber worldwide, bringing in new challenges for optical fiber makers. The optical fiber, getting closer to the end-users, is subject to more severe constraints and mistreatments during installations, resulting in crucial requirement for empowered resistance to external perturbations. To meet such demand, industry and standardization bodies teamed up efficiently to develop at an accelerated pace (2 years) a new standard for bend-insensitive single mode fibers, G.657, to be used in access network environments.

Such bend-insensitive single mode fibers have represented one of the major development focuses of optical fiber manufacturers for the last 5 years, with several options having been and still being investigated. Such options are ranging from mature and industrial technologies (solid-trench-assisted designs) to longer term technologies, holding promises for state-of-the-art performances but still facing homogeneity, industrial and competitive pricing issues.

Much has already been achieved in the optical fiber field, especially during last couple of decades, to reach this dramatically efficient transmission media, unrivaled in terms of capacity potential, immunity to external perturbations and resistance, which is now backing ever more efficiently human beings' lives.

And with new applications in sight in a variety of other domains than telecommunications, there is no doubt that the future holds a number of exciting technological challenges for optical fibers.

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