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C. R. Physique 4 (2003) 29–39

COMPTES RENDUS PHYSIQUE

Optical telecommunications/Les télécommunications optiques

Optical fiber design for wavelength-multiplexed transmission

Conception des fibres optiques pour la transmission multiplexée en longueur d'onde

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Received 3 October 2002

Presented by Guy Laval

Abstract

Optical fiber has evolved from a not-so-transparent glass tube to an extraordinarily efficient transmission medium. It is now acknowledged as a central element of modern telecommunication, being part of the whole optimization process to further improve transmission system performance and cost. In this paper, we briefly introduce key fiber characteristics. We then review the elements of fiber design for optimized optical transport networks and show how fibers have evolved over the last ten years to keep pace with more and more demanding requirement of transmission system. ***To cite this article: P. Nouchi et al., C. R. Physique 4 (2003).***

Résumé

Les fibres optiques ont évolué d'un simple tube de verre peu transparent à un moyen de transmission incomparablement plus efficace. Les fibres optiques sont maintenant reconnues comme un élément central des télécommunications modernes. Leur optimisation est essentielle pour continuer d'améliorer les performances et les coûts des systèmes de transmission. Dans cet article, nous rappelons brièvement les caractéristiques essentielles des fibres. Nous présentons ensuite les éléments clés de la conception des fibres pour optimiser les réseaux de communications, et nous montrons comment les fibres ont évolué pour s'adapter aux contraintes toujours plus fortes imposées par les systèmes de transmission. ***Pour citer cet article : P. Nouchi et al., C. R. Physique 4 (2003).***

Keywords: Optical transmission; DM; Optical fiber; Chromatic dispersion; Effective area; Dispersion compensation

Mots-clés : Transmission optiques ; Multiplexage en longueur d'onde ; Fibre optique ; Dispersion chromatique ; Surface effective ; Compensation de la dispersion

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1631-0705/03/$ – see front matter
doi:10.1016/S1631-0705(03)00003-3

1. Introduction

In the early 1960s, optical communication research activities benefited from the invention of laser to propagate light beams through optical lenses in free space or hollow tubes (1962). Although the principle of dielectric waveguides (Hondros and Debye, 1910), i.e., optical fibers, was theoretically more interesting, it was left apart because of tremendously high optical loss inside the material. In 1968 [1], Kao proposed to use fused-silica glass fiber as a medium for guided optical transmissions. Hence, *silica-based fibers* began to appear and in 1970, Corning Glass Works (USA) [2], demonstrated optical loss of 20 dB/km at a wavelength of 850 nm, that is 1% of injected signal power remains after 1 km of fiber. During the following decade, dazzling developments took place: the transmission window shifted from 850 nm to 1310 nm and finally to 1550 nm, while attenuation rapidly reached its minimum theoretical limit. Single-mode fibers exhibiting attenuations as low as 0.20 dB/km at 1550 nm [3], was demonstrated in 1979. In 1986, the value of 0.154 dB/km at 1550 nm was obtained for an SMF with a pure silica core and a fluorine optical cladding [4]. For fibers with germanium-doped core (i.e., 'standard'), with an intrinsically higher loss, 0.160 dB/km at 1550 nm were reported in 2000 [5]. The current absolute attenuation record is 0.152 dB/km at 1550 nm for a pure-silica core fiber (PSCF) [6].

Low-loss fibers are among the most dramatic developments that opened the door to fiber-optic communications subtending today's highly sophisticated *World Wide Web* (WWW), which links the whole planet in real time. The key benefit of fiber optics in telecommunications is *bandwidth*. It is orders of magnitude higher than in electrical, radio or microwave transmissions. Such 'virtually unlimited' bandwidth is crucial to feed WWW capacity demand. The maturity of components and system technologies have made optical systems evolve from *single-channel* transmissions regenerated every tenths of kilometers to *multi-channel* transmissions (wavelength-division multiplexed, or WDM) with ultra-high capacity over ultra-long, un-regenerated distances. Among these advances, the apparition of *erbium-doped fiber amplifiers* (EDFA) [7] in the late 1980s was critical for WDM viability by providing the ability to simultaneously optically amplify many wavelengths. Such an evolution changed the role of optical fibers in systems from a 'transparent pipe' to an active subsystem to account for in the global optimization process. Therefore, fiber providers must be familiar with transmission system requirements and be equipped with powerful simulation tools to adequately design transmission fibers.

This article reviews the elements of fiber design for optimized optical transport networks. Section 2 is dedicated to the key characteristics of fibers and the ways to model, compute and optimize them. Section 3 targets the optimization of transmission fibers, while Section 4 addresses the particular case of *dispersion-compensating fibers* (DCF), which must be associated with transmission fibers in the frame of high bit-rate transmission. The last section opens new perspectives by addressing 'futuristic' fiber designs.

2. Description of key fiber characteristics

Transmission fibers are long cylindrical strands (125 µm diameter) of silica glass. They essentially consist of a central core surrounded by a cladding: the core has higher refractive index n_{core} than the surrounding cladding n_{clad} ($n_{\text{core}} > n_{\text{clad}}$), thus allowing light to be guided. The *refractive-index profile* describes the change of index in the fiber's cross-section. The key fiber characteristics depend upon this refractive-index profile. Fig. 1 shows various index-profile shapes commonly used for single-mode fibers. The most simple one consists of a step, i.e., a core with a constant index of refraction. Typical value for core diameters are 10 µm. We see below that profile shapes have become increasingly complicated as fiber requirements are more stringent. Knowing refractive-index profiles, light propagation can be very well described by Maxwell's equations.

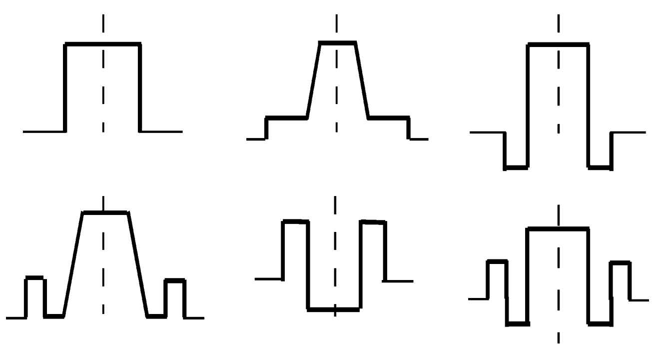

Fig. 1. Example of refractive-index profiles, commonly used for single-mode fibers. From top to bottom: step, pedestal, W, trapezoid+ring, coaxial, triple clad.

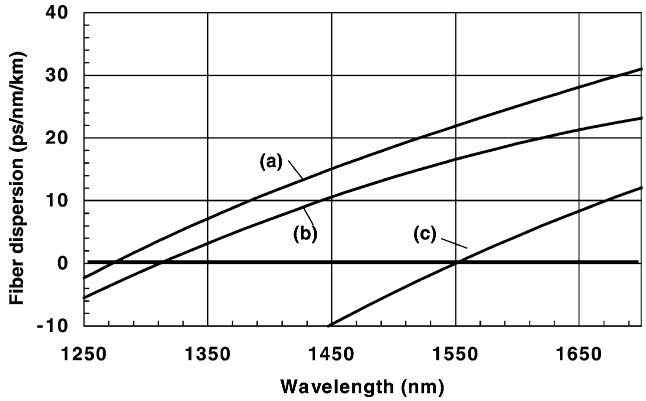

Fig. 2. Evolution of dispersion as a function of wavelength (a) material dispersion for silica, (b) standard single-mode fiber SMF, (c) dispersion shifted fiber DSF.

Fiber *manufacturing* is a two-step process. The first step is the fabrication of a high-purity rod of material called *preform*. This rod has exactly the same composition and cross-sectional profile as the fiber but its diameter is a few cm. Because of this large size, it is possible to control very well the index-profile shape. The core's index of refraction is raised through *germanium doping*. For more complicated profiles, the index can also be lowered through *fluorine doping*. Index differences with respect to silica are small, on the order of $\sim 10 \times 10^{-3}$. Preforms can be prepared using different techniques [8]: MCVD (modified chemical vapor deposition), VAD (vapor axial deposition) and OVD (outside vapor deposition). The second step consists in drawing the preform rod into the 125 µm fiber, which becomes an exact smaller-size replica of the rod. The rod is heated during fiber drawing from the end of the preform by gravity and a small pulling force. During drawing process, the fiber is polymer-coated to ensure mechanical protection. The coated fiber diameter is 250 µm.

We now review key single-mode fiber characteristics that impact on optical system performance, i.e., fiber loss, dispersion and effective area.

Fiber *loss* is a fundamental limiting factor as it reduces signal power propagating through the fiber. It is described by an attenuation coefficient α in dB/km. At 1.55 µm, where most systems operate now, typical coefficient values are 0.2 dB/km, close to the fundamental limit for silica. In this wavelength range, Rayleigh scattering is the main contribution.

Bendings constitute another source of loss. The smaller the bending radius, the higher the loss. When designing fibers, bending loss should be kept negligible for a bending radius above 10 mm. When fibers are in cable form, micro-bending loss can occur. Micro-bending corresponds to random axial oscillations. It happens when fibers are pressed against a surface that is not perfectly smooth. Again, when designing a fiber, micro-bending loss should be kept as low as possible, i.e., fiber cabling should introduce negligible loss.

Fiber *chromatic dispersion*, another key characteristic, causes light pulses to broaden because each wavelength travels at a different group velocity. Dispersion is given in ps/(nm·km). Dispersion exists in all dielectric materials and is related to refractive-index wavelength dependence. In fibers, dispersion has two contributions: that of silica itself, called 'material dispersion', and that of the guiding structure called 'waveguide dispersion'. Silica dispersion is shown on Fig. 2. It zeroes near 1.28 µm and is positive at longer wavelength ($\sim$20 ps/(nm·km) at 1.55 µm). On the other hand, waveguide dispersion is negative over a broad spectral range. Waveguide dispersion depends upon profile shape and can thus strongly modify fiber dispersion. While *standard single-mode fibers* (SMF) have dispersion curves very close to that of silica, other fiber types have very different dispersion curves, as shown on Fig. 2. The *zero-dispersion wavelength* λ_0 can be shifted to 1.55 µm for DSF (dispersion-shifted fiber) or near 1.55 µm for NZDSF (non-zero dispersion shifted fiber). Strong negative dispersion can also be realized near 1.55 µm, down to -100 ps/(nm·km) or less, for DCF (dispersion-compensating fiber). Fiber dispersion characteristics can be tailored through both careful index-profile choice and adjustment of profile parameters. Usually, fiber dispersion is defined in terms of zero dispersion wavelength, chromatic dispersion and *dispersion slope* (first derivative of dispersion with respect to wavelength) at 1.55 µm.

Another source of dispersion arises in single-mode fiber when circular symmetry is broken, yielding a slight birefringence and different group velocity for orthogonal polarization modes. It is referred to as PMD (*polarization mode dispersion*) [9,10]. Because fiber birefringence is small and varies in a random fashion along the fiber, PMD is not linear with length, but is given in $\mathrm{ps}/\sqrt{\mathrm{km}}$. PMD is now very well controlled in today's fibers and is well below 0.1 $\mathrm{ps}/\sqrt{\mathrm{km}}$.

The fiber *nonlinear effective area* (A_{eff}) is another key parameter for long-haul transmission systems. The effective area measures how much intensity can be handled in the fiber before impairments due to nonlinearity occur [11]. The material contribution of silica to nonlinearity is traditionally given by *nonlinear coefficient* n_2, which is about 2.7×10^{-20} m^2/W [12]. Fibers of SMF and DSF types have $A_{eff} = 80\ \mu m^2$ and $A_{eff} = 50\ \mu m^2$, respectively.

Finally, the *cut-off wavelength* λ_c, is a characteristic common to single-mode fibers, as it defines the wavelength boundary above which fibers are single-mode, i.e., for $\lambda > \lambda_c$. The *fundamental mode* is referred to as LP_{01}. Typical transmission fibers are single-moded above 1300 nm.

The knowledge of refractive-index profile and index-dependence with wavelength allows one to predict dispersion and mode-field characteristics. Scalar-wave equations, derived from Maxwell's equations in the weakly-guiding approximation, can easily be solved for arbitrary index profiles and wavelengths [13]. Once the propagation constant (or effective index) and fundamental mode-field distributions are known, effective area, chromatic dispersion, bending and micro-bending sensitivity parameters can be computed [14].

3. WDM influence on transmission fiber design

The apparition of WDM dramatically increased the use of the fiber transmission bandwidth. It opened the silica-transparency wavelength domain, typically from 1260 to 1675 nm. Standards (ITU-T) define possible spectral bands shown in Fig. 3. Beside the *conventional* (*C*) band [1530–1565 nm], five other bands were identified: the *original* (*O*) band [1260–1360 nm], the *extended* (*E*) band [1360–1460 nm], the *short* (*S*) band [1460–1530 nm], the *long* (*L*) band [1565–1625 nm] and the *ultra-long* (*U*) band [1625–1675 nm].

Combining high capacity with long transmission distances, thus obtaining high capacity-distance products, rests upon a critical choice of transmission fiber. To achieve long distances, designers must find a trade-off between two opposite limiting factors. On the one hand, input power needs to be high enough to overcome fiber loss, thus ensuring sufficient signal-to-noise ratios (SNR) at transmission end. On the other, nonlinearities degrade signals with high power densities (Fig. 4). In WDM, cross-nonlinearities, induce interference between neighboring channels, and are the most limiting ones. Their impact increases with narrower channel spacings, with smaller effective areas or with low (local) dispersion. The following constraints should then be considered in design optimization:

- Optical fiber characteristics must be optimized for a broad wavelength range and not only at 1550 nm. A typical attenuation spectrum is shown in Fig. 3. It appears that *S*, *C* and *L* bands are compatible with low attenuation requirements. Fibers with lowered 1385 nm-peak (due to residual hydrogen, yielding Si-OH vibration) have been unveiled to open the *E* band [15]. Concerning the *U* band, an attenuation increase is observed. This is the tail of the multi-phonon silica absorption peak in far IR. Micro- and macro-bending loss might also occur since it increases with wavelength. Fiber design requires controlling these parameters to enable operation at the longest wavelength band. Second, λ_c must be under the lowest operating wavelength to avoid higher-order mode propagation. Finally, it is essential to keep the dispersion slope as close as possible to zero.
- Fiber dispersion is another essential parameter to optimize. Fibers with λ_0 in the operating wavelength region (DSF) were before considered as a very attractive alternative to minimize dispersion accumulation. They are now excluded with WDM.

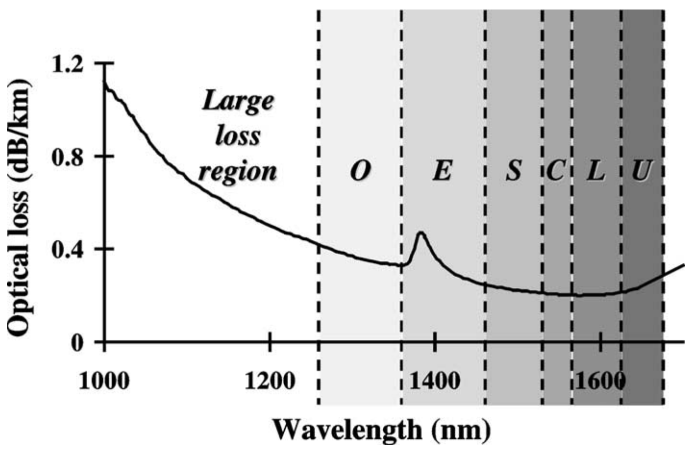

Fig. 3. Attenuation as a function of wavelength and transmission bands according to ITU-T definition (Original (*O*), Extended (*E*), Short (*S*), Conventional (*C*), Long (*L*) and Ultra-long (*U*) bands).

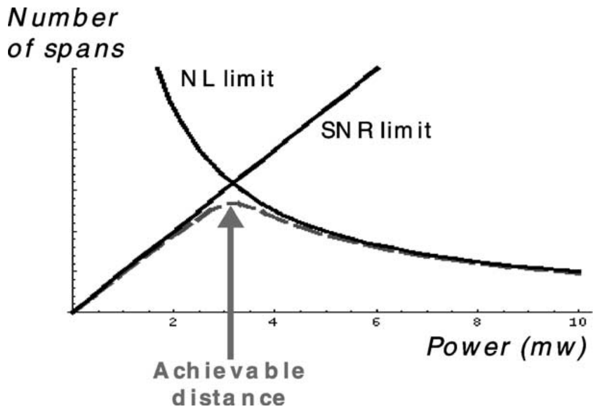

Fig. 4. Nonlinear limitation versus SNR limitation dilemma.

Table 1
Typical transmission fiber characteristics at 1550 nm from various suppliers

		Dispersion [ps/(nm·km)]	Slope [ps/(nm^2·km)]	λ [nm]	A_{eff} [µm^2]
NZDSF family	Enhanced LEAF™ [17]	4	0.085	1500	72
	TrueWave® RS [18]	4.5	0.045	1450	55
	TeraLight Ultra™ [19]	8	0.052	1405	63
SMF family	SMF	17	0.058	1310	80
	Z-PLUS Fiber™ [20]	20.5	0.059		110

Indeed, it is now widely recognized that a small amount of dispersion is needed to counteract nonlinear effects between closely-spaced channels, hence the introduction of NZDSF. The SMF, with its large dispersion (17 ps/nm/km) in the 1550 nm window, is more suitable as it drastically reduces the cross-nonlinearity impact. At high channel bit rate, such as 10 Gbps or over, nevertheless, DCF is required in the transmission line to prevent dispersion distortions. This impacts both the system cost and the output SNR, due to extra loss from the DCF. The NZDSF, with intermediate dispersion values are an interesting alternative because they limit the required DCF length while providing fair resistance to nonlinearity.

– The fiber effective area must be maximized to limit nonlinearity. However, *stimulated Raman scattering* (see article by D. Bayart in this issue) is a nonlinear effect which can be advantageously used for *distributed amplification*. Targeting only high effective-areas is therefore not appropriate to take advantage of this beneficial nonlinearity while suppressing detrimental ones. In this case, higher dispersions with medium effective areas is the successful compromise.

When targeting NZDSF characteristics, simple step-index profiles are no longer sufficient: indeed, a high index difference is required to obtain larger waveguide dispersions than in standard SMF, yielding optical-field confinement and small effective areas. To overcome such a problem, multi-layered core indexes have been proposed with *pedestal*, *trapezoid + ring* or *coaxial* shapes [16]. Larger effective areas are then obtained at the expense of more complicated profile structures. The same way, waveguide dispersion slope, and hence dispersion slope, can only be customized by using a multi-layered structure. For a given profile-shape family, the effective area is unfortunately proportional to the dispersion slope, thus leading to possible trade-offs: a large A_{eff} with high dispersion slope [17] or a small A_{eff} with small dispersion slope [18]. A dispersion increase from 4–8 ps/(nm·km) allows one to improve the A_{eff}/slope trade-offs as well as to reduce sensitivity to optical cross-nonlinearity [19]. Table 1 summarizes results of some commercially-available NZDSF fibers, illustrating such trade-offs.

When targeting high chromatic dispersion like in SMF, waveguide dispersion is low and does not significantly impact upon dispersion slope, even with a multi-layered structure. In this case, the slope is near 0.06 ps/(nm^2·km), which is that of the material. Note A_{eff} in SMF is larger than in NZDSF. Competitors proposed fibers belonging to the SMF family with greater A_{eff} (Table 1). Such improvement is mainly due to a cutoff wavelength increase and definitely prevents the fiber from being operated in shorter wavelength bands.

According to recent results from many research teams, the optimum dispersion value is in the range of 6–11 ps/(nm·km) at 1550 nm [19,21–25], see Table 2. Propagation characteristics have been improved: the dispersion slope stays lower than 0.07 ps/(nm^2·km) with a minimum at 0.031 ps/(nm^2·km) and A_{eff} is always greater than 50 µm^2, with a maximum at 96 µm^2 for

Table 2
Transmission fiber characteristics of recent prototype fibers

	Dispersion [ps/(nm·km)]	Slope [ps/(nm^2·km)]	λ [nm]	A_{eff} [μm^2]
[21]	7.5	0.042	1385	55
[22]	9.1	0.065		96
[23]	10.8	0.060		70
[24]	8.9	0.031	1350	55
[25]	6.5	0.035	<1400	55

this dispersion range. These fibers, with λ_0 values lower than the S band lower-bound, are WDM-compatible in $S+C+L$-bands and give very flat dispersion-managed link as we shall see in the following.

4. Evolution of dispersion-compensating fibers

As seen in the previous section, transmission fiber optimization for optimum WDM operation is quite complex. Compensation of accumulated dispersion is also a key factor. At present, the preferred technology is the *dispersion-compensating fiber* (DCF) with high negative chromatic dispersion.

Using a DCF was first proposed in 1980 [26], but it was only after the advent of EDFAs in 1990 that the development of DCF accelerated [27–31]. Indeed, upgrading installed 1310 nm-optimized standard SMFs to operate in the EDFA's 1550 nm-window, where dispersion is near 17 ps/(nm·km), raised the need for dispersion compensation. More recently, with the increase in bandwidth (WDM), in bit-rate (⩾10 Gbps) and distance (⩾500 km on land) in optical networks, the requirements for dispersion compensation have become more stringent and impressive improvements were made in DCF development [32–36]. In the last three years, new DCFs adapted to all transmission fiber types over wide spectral ranges have been introduced [24,37–42].

Basically, DCFs are designed so that the fundamental mode is weakly guided. A large fraction of the mode propagates in the cladding where the refractive index is lower. The waveguide contribution to the chromatic dispersion is thus relatively large in such fibers, resulting in high negative dispersion, i.e., $\leqslant -100$ ps/(nm·km). Unfortunately, the weakly-guiding condition imposes fiber cores to have small diameters (<5 μm), and a high refractive-index difference ($>15\times10^{-3}$), and DCF suffers from high loss, and small effective area. A DCF is also more sensitive to small core-index fluctuations and to core ovalities than SMFs or NZDSFs. Fiber manufacturing must be careful to tightly control longitudinal and radial core homogeneities and hence dispersion and PMD [32,36].

Considerable work was performed to address these issues and improve the DCF performance.

First studies concentrated on DCF *loss*. The extra loss introduced by DCFs, when used in modules for discrete compensation at the amplifier locations, not only depends upon the loss but also on the length, i.e., the net ps/nm dispersion. A commonly-used *figure of merit* (FOM) for DCFs is the ratio of the absolute value of dispersion to fiber loss (ps/nm/dB). However, one must be careful when using this reference because high FOMs can be associated with high bending sensitivities [33]. This can cause loss increase when spooling conditions are more stringent or when wavelength increases, making DCFs unsuited for modules [37]. In 1996, the highest reported FOMs using practical conditions were around 300 ps/nm-dB with chromatic dispersion ranging from −150 to −100 ps/(nm·km) [34,35], while in 2001 the record was at 460 ps/nm-dB with a high negative chromatic dispersion of about −300 ps/(nm·km) [38].

To achieve optimum WDM system performance, DCFs must not only compensate for dispersion at a given wavelength but also at all wavelengths. This implies that both dispersion and *dispersion slope* should be negative. The narrow high-index step was the first and most simple index profile used for DCF but it could not achieve negative-dispersion slopes. Adding a depressed cladding next to the central core ('W' profile, see Fig. 1) provides a better control as a function of wavelength of the waveguide contribution to the chromatic dispersion and negative-dispersion slopes can be obtained [30,34,35]. To improve the bending sensitivity, a ring surrounding the depressed region can also be included [29,31,36], yielding a *triple-clad* profile type (Fig. 1).

To keep pace with the increasing bit-rates and transmission distances of WDM systems, dispersion-compensation techniques have become increasingly accurate. A DCF must now be optimized for a given transmission fiber, i.e., standard SMF or 1550 nm-optimized NZDSFs. It is therefore useful to define a new parameter: the *dispersion over slope ratio* (DOS), specified at some wavelength, usually centered in the bandwidth mid-point [30,35,37]. To achieve slope compensation, the DCF-DOS must match that of the transmission fiber, resulting, after compensation, in a relatively flat dispersion over the entire bandwidth. By changing the width and the index difference of the depressed cladding surrounding the central core, it is possible to adjust the DCF-DOS. It ranges from 50 nm for DCFs compensating some NZDSFs up to 300 nm for DCFs adapted to SMFs. DCFs with small DOS, i.e., having high negative-dispersion slopes, exhibit wide and greatly depressed claddings, which leads to high bending sensitivity and small effective areas [42]. On the other hand, DCFs with high DOS offer desirable properties such as high FOMs and good tolerance to nonlinearity.

Managing dispersion and dispersion slope results in flat dispersion only over limited bandwidth (typically $\Delta\lambda = 40$ nm). For wider bandwidths, variations of the slope itself must be considered. Indeed, dispersion does not vary linearly as function of wavelength, especially dispersion of DCFs having high negative dispersion slopes. The DOS is insufficient to describe how well a DCF matches a transmission fiber within a wide bandwidth. A more relevant parameter is the *maximum chromatic dispersion* of the compensated link [24,39]. Tight adjustments of index-profile parameters have enabled to control slope variations as a function of wavelength, yielding maximum link dispersions below 0.1 ps/(nm·km), over both C and L bands, as recently reported [24,40,41]. The smallest values correspond to the highest DOS (50 nm-DOS links for example exhibit maximum dispersion around 0.1 ps/(nm·km) over one band [39,42]). Given a dispersion tolerance of about 60 ps/nm in 40 Gbps transmission [43], over 500 km can be spanned with high-DOS links without per-channel dispersion trimming and without bandwidth gaps from 1530 to 1610 nm. These recent achievements seem very promising for future high bit-rate ultra long-haul transmission [44,45].

Another dispersion-compensation scheme consists in developing *dispersion-managed* (DM) *cables* based upon mixing in each individual span a positive-dispersion fiber, as described in Section 3, and a negative-dispersion one. Such compensating fibers, deployed in cable as regular transmission fibers, are usually referred to as *reverse-dispersion fibers* (RDF) [46–48]. These RDFs exhibit smaller absolute-dispersion values than standard DCFs, the magnitude being commonly twice greater as that of the associated positive-dispersion fiber. Refractive-index profiles of RDFs present similar shapes as those of DCFs, though with smaller index differences. This leads to attenuation values smaller than 0.3 dB/km. DM-cables have originally been used in submarine transmission, yielding terabit/s capacities over transoceanic distances [49,50]. More recently, the technology has also been used in ultra-long-haul terrestrial transmission experiments [51].

5. Promising technologies

Research in the area of silica-based fiber is still very active. In this last section, we provide a brief overview of highly innovative research work which could prefigure tomorrow's fibers, namely: DMF *dispersion-managed fibers* (DMF), *high-order-mode fibers* (HOM) and *photonic-crystal fibers* (PCF).

In previous sections, we saw how dispersion management is essential to achieve efficient WDM transmission. A current approach is to use two fiber types: NZDSF for the transmission fiber and DCF to periodically compensate accumulated dispersion. An alternative solution, proposed in the late 1990s [52–55], consists of a single fiber with alternating sections of positive and negative dispersion directly built-in into a continuous fiber. The axial dispersion variation is characterized by a *dispersion map* with period L_p, which is in the order of a few kilometers. Dispersion values are usually between 1 and 8 ps/(nm·km) (-8 and -1 ps/(nm·km)) for the positive-dispersion (negative-dispersion) sections.

Management of dispersion is thus continuously built-in in DMFs, i.e., without any splices, but manufacturing remains a challenge. Several techniques have been developed [54,55] to periodically vary the fiber index profile along its longitudinal direction. For example, the fiber core diameter can be periodically changed [54]: this either upon drawing, with a constant-diameter preform, or during preform manufacturing with constant fiber diameter. In [54], the fiber presents not only alternating dispersion, but also alternating dispersion slope, yielding a very flat overall dispersion over a wide band (0.006 ps/(nm^2·km) between 1500 and 1600 nm). Authors also demonstrated *soliton* transmission of 1×100 Gbps over 1000 km of such fiber (see article on solitons by Turitsyn et al., in this issue).

All the fibers we have described so far are single-moded, i.e., only one spatial/transverse mode is supported by the fiber in the operating window. On the contrary, HOMs are few-moded fibers, being operated in such a way that only one higher-order mode is excited (LP_{02} or LP_{11}). The underlying idea is that with proper index-profile design, higher-order modes can present unmatched propagation characteristics compared to the fundamental mode. This is especially true for dispersion-compensation applications, where both high negative dispersions (well below -100 ps/(nm·km)) and high negative dispersion-slope values can be reached.

The first HOM realization for dispersion compensation modules appeared in the early 1990s, with the demonstration of record dispersion of -228 ps/(nm·km) at 1.55 µm [56]. This technique requires mode converters to selectively excite the higher-order mode from the incident LP_{01} mode of the transmission fiber and the reverse, as illustrated in Fig. 5. Mode conversion has been achieved through various techniques, such as: grating coupling through periodic micro-bending [56,57] or photo-induced change (Bragg grating) [58], and free-space optics [59].

To recall, the main advantage for this technique is that large negative-dispersion values can be obtained (<-200 ps/(nm·km)). The compensating fiber length required is shorter, and so is module loss, providing that converters do not introduce too much loss. Another advantage is that the effective area of HOM is quite large compared to conventional DCF [60]. However, the multimode nature of this device does have some drawbacks: complexity of the module and possible interference between the

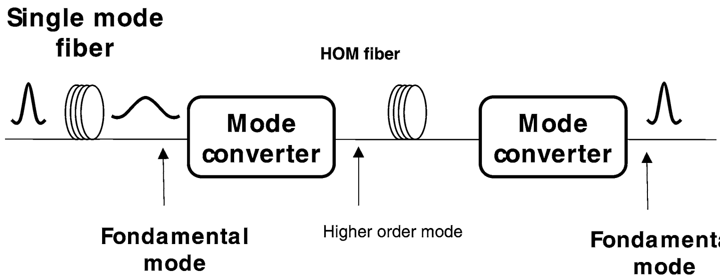

Fig. 5. Principle of operation for HOM-based dispersion compensating modules.

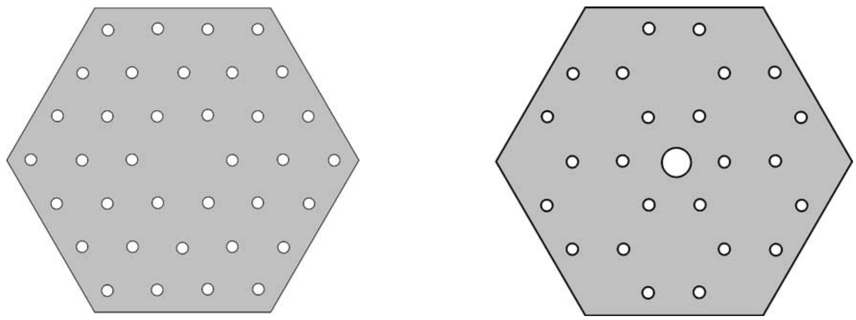

Fig. 6. Schematic of Photonic Crystal Fibers: TIR-PCF (Total Internal Reflection) on the left and PBG-PCF (Photonic Band Gap) on the right.

modes within the HOM. This last feature is characterized through the *multi-path interference* (MPI) value, expressed in dB [61]. A few interesting transmission experiments have been achieved with HOM-based modules, e.g., 1×40 Gbps over 3×80 km of NZDSF fiber [62] and 1×40 Gbps over 17 100 km on NZDSF [63].

The last type of fiber we review is the PCF. These fibers are still made from silica glass, but they include regularly- (or irregularly-) spaced *longitudinal air holes*. The large index difference between silica and air, the size of holes being of the order of the wavelength and their transverse periodicity allow very unusual propagation characteristics, which are out of reach in conventional fibers.

Two very different PCF types are commonly investigated: *total internal reflection* (TIR-PCF) and *photonic band-gap* (PBG-PCF), as illustrated in Fig. 6. In the first type, center is 'filled' with silica and light wave-guiding is achieved the classical way with a cladding refractive index lower than the core index. A first realization was demonstrated in 1996 [64]. In the second type, the fiber includes a central hole which confines light through the *photonic band-gap effect*. Wave-guiding results from a periodic and micro-structured cladding, in which guided propagation in a certain wavelength range is 'forbidden' [65]. Its first realization is described in [66]. Both fiber types are usually made by stacking an array of hollow silica rods to form the preform, which is then drawn into a fiber.

The new PCF structures allow a wide range of characteristics that cannot be reached by standard fiber technology. Single-mode behavior has been observed over wider bandwidths ('endlessly single-mode') [67], as well as either very tight or very large effective areas (1 μm^2 to 1000 μm^2) [68]. Unusual dispersion properties have also been predicted/demonstrated: high negative dispersion [69], zero-dispersion wavelength shifted well below 1 µm [70,71] and flat dispersion over broad spectral ranges [68].

All those unusual features make possible a wide array of application: transmission or compensation fibers, highly linear or nonlinear fibers, and component fibers (sensors, amplifiers, birefringent fibers, etc.). However, practical realization is critical. Issues such as splicing, mechanical strengthening, realization of long lengths, bending/micro-bending loss still need to be addressed. Very low loss has not yet been demonstrated, although rapid progress is made. In the late 1990s, the first fibers exhibited a few 100 dB/km, while impressive 'under-1 dB/km' fibers have been reported in 2002 [72,73].

6. Conclusion

To keep pace with capacity demand, transmission technologies are doomed to constant progress, thus dramatically increasing the data rates that can be handled by fibers. Such rates are constantly pushing the physics of guided-light propagation closer to new limits. Therefore, fibers are now be part of the system-optimization process, as opposed to mere 'dummy' light-pipes.

For global optimization, *system requirements* must first be well identified before being translated into *fiber requirements*. Fiber loss must be controlled for proper operation throughout all transmission bands of interest, meaning constraints on cut-off wavelengths, on micro/macro-bending loss as well as OH-peak attenuation. The trade-off between dispersion and effective area is also very important to manage detrimental nonlinearity. Finally, another crucial compromise (also system-imposed for broadband operation), is the one between effective area and dispersion slope. All these compromises must be made both in transmission fibers and compensation fibers, further adding to the complexity of fiber design.

This article reviewed the different options fiber designers must control to get as close as possible to optimum fiber characteristics. In this new fiber generation, the index profile shapes have evolved from simple step-index towards multi-layered core-indexes with pedestal, trapezoid+ring or coaxial ones. Research is also very active in the field of compensating fibers to meet system requirements on dispersion/dispersion-slope compensation, as well as on dispersion management over the widest achievable bandwidth. Furthermore, such performance must be achieved together with relatively low loss and large effective areas. Compensating fibers to matching existing transmission-line fibers, have been produced with excellent performance. Thanks to great advances in fiber design, optimized new-generation fibers for transmission and compensation could be developed and enabled countless lab transmission records of many *terabits-per-second* over *thousands of kilometers* (see article by S. Bigo et al., in this issue).

What is the next step? It might be possible to go beyond such tremendous capacity with the futuristic designs under current investigation. Among these new research activities, promising ones are fibers with intrinsic dispersion-management, dispersion-managed fibers, photonic-crystal fibers and higher- order-mode fibers. Such designs, if applicable to transmission fibers and compensation, could provide extra system flexibility and offer new trade-offs that will be beneficial to improve transmission quality and capacity.

In summary, evolving from a not-so-transparent glass tube to an extraordinarily efficient transmission medium, the optical fiber is world-widely acknowledged as a central element of modern telecommunication systems. Therefore, the fiber now forms an integral part of overall system optimization. Thanks to advances in fiber technology, universal and real-time communications are now a reality which can be accessed at affordable prices by private end-users. A key challenge is to keep the technology always progressing while providing lower-cost solutions to network operators.

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