12th Optoelectronics and Communications Conference/16th International Conference on Integrated Optics and Optical Fiber Communication (OECC/IOOC2007)
Technical Digest, July 2007, Pacifico Yokohama

12C1-1 (Invited)

New fiber designs and fabrications for data transmission and novel fiber devices

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Abstract

We review some recent results on novel fibers for both transmission and devices, covering bend-insensitive fibers, compensating fibers, highly non-linear fibers and Er-doped fibers.

Introduction

Optical fiber landscape has been constantly evolving. The last few years have witnessed the penetration of fibers deeper into the network with Fiber To The Home (FTTH) applications now booming. In the field of components, more and more applications are foreseen for specialty fibers, that can be telecom, as well as non telecom based.

Research in fiber area is very active to keep pace with this wide variety of demanding requirements. It is the purpose of this paper to review current research works for some key applications. In the field of transmission, advanced fibers have been developed to meet the specific requirements of FTTH ; compensating modules have evolved to account for stringent Ultra Long Haul (ULH) system constraints. On the component side, PCFs (Photonic Crystal Fiber) have clearly paved the way to realize improved non-linear optical fibers that can target a large range of applications. At last, we will cover recent advances in the fabrication of Er-doped fibers.

Bend-insensitive fibers for access applications

FTTH is now a reality with transmission needs of 100Mb/s or more. This has spurred the development of fibers exhibiting reduced bending sensitivity compared to today Single Mode Fibers (SMF), to better account for FTTH specific needs. Lower volume at the storage points, as well as increased resistance towards incidental bends originating from improper fiber deployment, and sharp bent for installation in corners are indeed required.

For classical step-index SMF, well-known solution to reduce bending sensitivity consists in decreasing the mode field diameter over cutoff wavelength ratio (MAC value) by increasing cut-off wavelength and/or decreasing mode-field diameter [1-3]. 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.652 standard -that guarantees well-defined ranges of values-.

This is the reason why other types of structures have been proposed over the past few years. Trench-assisted solutions [4, 5] consist of a classical step-index core with a cladding that includes a depressed layer (so-called "trench"). It is possible to find an optimized trench design that improves the fundamental mode confinement without reducing its mode field diameter; yielding significant reduced bending sensitivity while keeping G652 compatibility. Fibers compatible with both ITU-T G652.D and new G657A&B recommendations, have been demonstrated with such type of structure [5]. One main advantage of "trench" solutions is their compatibility with mature process deposition technologies, such as versatile PCVD (Plasma Chemical Vapor Deposition); thus enabling large-scale production. Hole-assisted solutions are interesting alternatives [2, 4]. Trench layer is here replaced with air-holes structure in the cladding. Air-holes physical impact is similar to the trench one but it could bring solutions with even more bend insensitive performances in the future.

System constraints on DCM design

At present, fiber-based dispersion-compensating module (DCM) is the preferred technology to achieve the robust dispersion management required in terrestrial WDM systems. In the past few years, major progress has been made in DCM developments, in order to account for always evolving ULH system constraints [6-9].

In [8], we established a simple analytical expression of the achievable distance of WDM systems as a function of both insertion loss and non-linearity of DCMs. We showed that the most efficient way to increase the system performance was to design dispersion-compensating fibers (DCFs) with high negative dispersions. Reaching values of -250ps/nm-km at 1550nm allows to gain ~15% (resp. ~5%) in distance for G652 (resp. G655.D) fiber-based systems compared to typical -100ps/nm-km value. The drawback is that decreasing dispersion can alter both PMD and residual dispersion (RD) that also have impacts on system performance [9].

As a general rule, it is more difficult to manufacture DCFs when the dispersion is more negative, and especially with respect to PMD. But nowadays typical values of less than 0.10ps/√km can be reached through tight controls of the manufacturing process, even at -250ps/nm-km [6]. Besides, systems tolerate a fixed cumulated DCF PMD (linked to the ~10% bit-time limit that also includes contributions of line fiber and amplifiers) and moving from -100 to -250ps/nm-km allows to gain a factor of √(250/100)~1.58 on the maximum DCF PMD value. As a consequence and to a certain extent, there is no real PMD drawback when one targets more negative dispersion to improve system performance.

Concerning the RD, the situation is more complex because it depends on the dispersion-over-slope ratio (DOS) of the line fiber. Decreasing the dispersion has an impact on the RD of high-DOS DCMs (that is for G652 fiber compensation), but RD stays small anyway, within ±0.05ps/nm-km over the C+-band [6,9]. For low-DOS DCMs (that is for G655.D fiber compensation), decreasing the dispersion hardly influences the RD that remains high within ±0.25ps/nm-km over the C+-band (see Fig.1). Taking into account this effect, we find that, at 40Gbps bit-rate, reaching -250ps/nm-km for high-DOS DCM reduces the gain in distance from ~15% to ~10%

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compared to -100ps/nm-km, whereas for low-DOS DCMs the gain stays ~5% [8, 9].

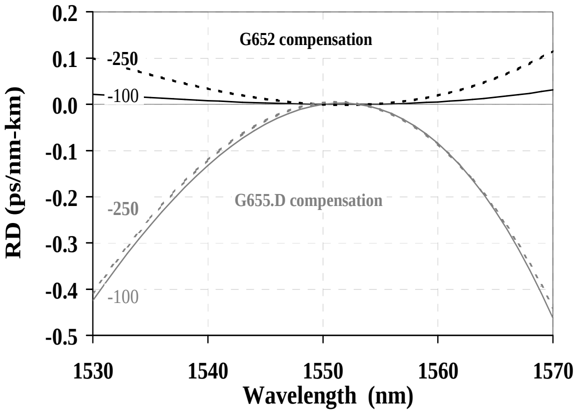

Fig. 1: RD as a function of wavelength for -100 (solid curves) & -250ps/nm-km (dashed curves) dispersion and for G652 (black curves) & G655.D (gray curves) compensation.

Highly non-linear fibers

Highly non linear fibers (HNLF) have attracted a lot of attention either for telecom (all optical signal processing, parametric or Raman amplification) or non telecom applications (white light sources, fiber Raman lasers).

Most of HNLFs are derived from SMF by modification of both the guiding parameters and the material non linear parameter. Higher index contrast and smaller core diameter lead to a strong reduction of the effective area. Whereas the corresponding increase of Ge (germanium) content in the core also allows to increase the n_2 coefficient. Best fiber, using conventional technology, has Ge concentration of more that 40wt%, effective area in the range of 10µm², yielding non linear coefficient γ of about $20W^{-1}km^{-1}$ and loss of 0.5dB/km [10]. Nevertheless there are some limits to such modifications and chromatic dispersion properties can only be tailored within a limited range of wavelengths.

To get even higher non linearities, shifting from silica-based fibers to fibers made from multicomponent glasses, such as Bismuth-based, telluride or chalcogenide glasses, has also been extensively studied. Nevertheless such fibers suffer from much higher loss and practical issues like reliability and splicing to SMF. These can represent some drawbacks, essentially for telecom applications.

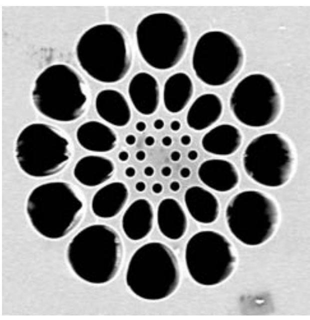

Fig. 2 : Highly-non linear PCF (A_{eff}=5 µm^2) with a close-to-zero matched chromatic dispersion [12].

The potential of Photonic Crystal Fibers (PCF) to enhance nonlinearities has been recognized at an early stage of their development. This is essentially due to the high index contrast between air and silica that allows to further decrease the Effective Area. Values as low as a few µm^2 have been reported. Doped rod in the core can be used as well to enhance non-linearities [11]. Even if loss is still a limiting issue compared to classical-technology fibers, PCFs can be designed to truly adjust chromatic dispersion properties. For example, zero chromatic dispersion wavelength λ_0 can be adjusted from visible up to telecom bands [12].

Erbium-doped fibers

Erbium Doped Fiber Amplifier (EDFA) is widely acknowledged as a key technology that has enabled the dramatic capacity increase from Gbit/s to Tbit/s, witnessed over the last decade in telecom applications. It has spurred the development of WDM technologies and the extensive use of dispersion management.

EDFAs are based on specific Erbium-Doped Fibers (EDF) that allow optical amplification through WDM window thanks to the incorporation of aluminum in the vicinity of the active Rare-Earth dopant. Further doping with aluminum allows unmatched properties [13]. Most common process to manufacture such fibers involves incorporation of Er and Al in a porous core layer through a preform-soaking step, as these elements are very difficult to incorporate using vapor-based processes.

However, today doping technologies -based on soluble chloride precursors mixing- have achieved their limits in terms of doping homogeneity and capabilities. In this frame, nanotechnology is now offering new potentialities thanks to molecular engineering that allows to define and finely build Er chemical environment in a preliminary nanoparticle (NP) manufacturing stage. It is then possible to introduce these NPs into fiber core using an innovative doping concept [14]. By using NPs that include Al and Er ions, the EDFA gain shape of classical highly aluminum-doped EDFs can be achieved using far less aluminum, and with an improved Er doping homogeneity all along the fiber. Such performances pave the way for even flatter and wider gain EDFA by using a smart selection or Er ions co-dopants.

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