Nano-Engineered Optical Fibers and Applications

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Abstract: This paper reviews a technology for making nano-engineered optical fibers. Key features and advantages of nano-enginneered glass fibers are discussed. Fiber designs and their applications are presented.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2270) Fiber characterization

1. Introduction

Since successful demonstrations of optical fibers with photonic crystal cladding in the late 1990s [1-2], photonic crystal fibers have attracted significant research interests in the past 10 years. Photonic crystal structures can offer significant advantages over conventional fiber structures in fiber designs, as air holes have a much lower refractive index and different dispersion properties than those of the silica glass, thereby offering a number of interesting physical effects that do not exist in conventional fibers. Both the bandgap guiding and average index guiding mechanisms have been extensively studied in the literature. Periodicity of the holey structure is essential for the bandgap guiding [2], but is not critical for the average index guiding [3]. In particular, it has been demonstrated that light can be guided in fiber with randomly distributed air holes cladding [4-5]. However the typical process for making photonic crystal fibers using the stack and draw process [6] is much more complicated than conventional fiber making processes, making the fibers less attractive for large scale and cost-sensitive applications.

We have reported a new nano-engineered fiber for Fiber-to-the-Home (FTTH) applications [7-8]. The fiber uses the nanoStructures® technology in its fiber design and can be manufactured using a standard Outside Vapor Deposition (OVD) process. In this paper, we will give an overview of nano-engineered fibers made using this new technology and discuss their applications.

2. Nano-engineered glass features and fabrication

Nano-engineered fibers contain nanometer-sized gas filled voids in the cladding that are incorporated in the glass during the fiber processing. Figure 1 shows a SEM picture of a nano-engineered optical fiber. The fiber shown consists of 20 μm diameter void-free silica core, with non-periodically distributed voids in the silica cladding. The cross-sections of the voids are circular and have diameters ranging from several dozens to several hundreds of nanometers. The void fill fraction can be designed to be between 1 to 10 percent. The voids are sealed and non-periodically distributed along the fiber length with void lengths ranging from less than one meter to several meters. The size characteristics of voids and void fill fraction significantly affect the optical properties of the nano-engineered region, thereby influencing the fiber performance.

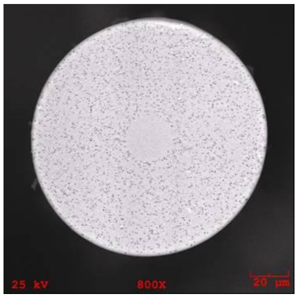

Figure 1. SEM picture of a fiber with nano-engineered cladding

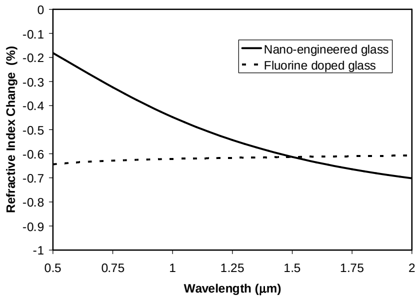

Figure 2. Comparison of refractive index changes of nano-engineered and fluorine doped glass.

The nano-engineered glass fibers offer several advantages compared to conventional glass fibers. First, the wavelength dependence of glass refractive index having nanometer sized features is very different from that of glass with conventional index lowering dopants (such as fluorine) used in fiber manufacturing. To illustrate this, we have modeled the effective refractive index of glass with periodically distributed nanometer-sized voids. The effective index is calculated from the propagation constant of the fundamental space-filling mode β_{FSM} by $neff = \beta_{FSM}/k$, where $k=2\pi/\lambda$ is the propagation constant of light in the free space [9]. To determine the fundamental space-filling mode, we use a vectorial finite element method to solve Maxwell equations within a unit cell of a periodic structure. Two periodic structures are modeled: triangular lattice and square lattice. It is found that the choice of structure of lattice is almost negligible in altering the effective index value. The effective index is mostly determined by the void size and the void fill fraction. Figure 2 compares the relative refractive index changes as a function of wavelength for a nano-engineered glass with voids and silica glass doped with fluorine. For the nano-engineered glass, the diameter of voids is 400 nm and the void fill fraction is 2.5%. For the fluorine doped glass, the fluorine doping level is about 2.2% by weight. It can be seen that the refractive index of nano-engineered glass has much stronger wavelength dependence than that of fluorine doped glass. The index change for nano-engineered glass increases with wavelength, while the index change for fluorine doped glass is nearly flat. The random distribution of void diameters also affects the wavelength dependence of effective index. A statistical analysis indicated that the random distribution of voids enhanced further the wavelength dependence. The wavelength dependence can be used to design fibers with low cutoff wavelengths.

A second advantage of nano-engineered fibers is that large negative index changes can be made with nanometer sized features. A relative index change as high as several percent can be achieved by using a nano-engineered design. Such a high index change is very difficult to realize using the conventional fluorine doping technology. This feature can be used to design fibers with high numerical apertures.

Thirdly the scattering property of a glass having nanometer-sized voids also has strong wavelength dependence. Light at shorter wavelengths has higher scattering losses than at longer wavelengths. This feature facilitates the suppression of higher order modes in nano-engineered ring assisted bend insensitive fiber designs.

The most important advantage of nano-engineered fiber is that they are much easier to make than photonic crystal fibers using the stack and draw process. A nano-engineered fiber can be made using OVD process. To make a nano-engineered glass cladding, silica soot is deposited on the glass core cane first. Then the soot preform is sintered in a consolidation furnace at fast sinter rates in a low permeability gas atmosphere at a peak sinter temperature of around 1500 °C to form a glass cladding containing voids. Additional silica soot can be deposited on the preform and then consolidated in a helium atmosphere to produce void-free outer region of the final optical perform. In the draw process, the voids are stretched into thin elongated voids. Because the process for making nano-enginneered fibers is compatible with the OVD process, it is suitable for large scale production.

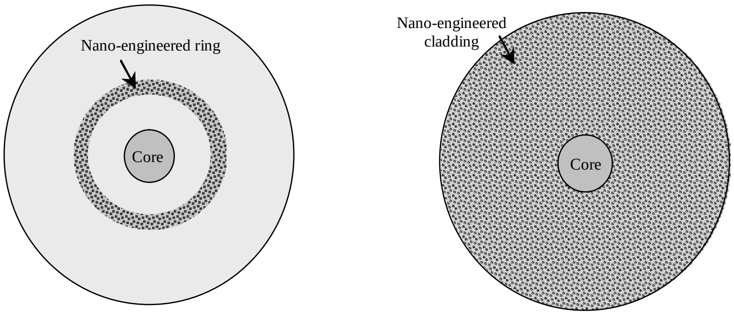

Figure 3. Schematics of two nano-engineered fiber designs.

3. Nano-enginneered fiber designs and applications

The unique features of nano-enginneered glass allow us to design fibers for different applications. Figure 3 shows schematics of two fibers designs. The first design consists of a germania-doped core and a nano-engineered ring in the cladding. This design offers very low bending loss while keeping the other optical parameters fully compliant with the ITU-T G.652 standards, which is suitable for making bend-insensitive fiber for FTTH applications. Modeling results show that the nano-engineered fiber has 1550 nm bending loss of less than 0.1 dB/turn at 5 mm bend radius, about 10 times lower than the typical fluorine trench fiber. We made fibers using the OVD process and demonstrated this design is suitable for large scale production. Typical measured optical properties of the fiber are fully compliant with the G.652 standards. Typical bending loss at 5 mm radius is 0.03 dB/turn at 1550 nm wavelength. Figure 4 compares typical bend losses as a function of bend radius for the fiber with nanometer sized features, standard single-mode fiber and trench fiber at 1550 nm. This figure shows that the nano-engineered fiber has about 500 times lower bending loss than the standard single-mode fiber, and 6-10 times lower than fluorine trench fibers. Quasi single-mode fibers were also made with wider void-containing rings using nanoStructures technology. These fibers have similar mode-field diameters as standard single-mode fibers (8.2-9.5 µm at 1310 nm). While these fibers have cable cutoff above 1260 nm, they can be used as a single-mode fiber if a restricted launch into the core is used. Measured bending loss of this fiber shown in Fig 4 is less than 0.01 dB/turn at 5 mm bend radius and less than 0.001 dB/turn at 10 bend radius, comparable to the bend losses of the hole-assisted bend resistant fibers reported in [10] and [11].

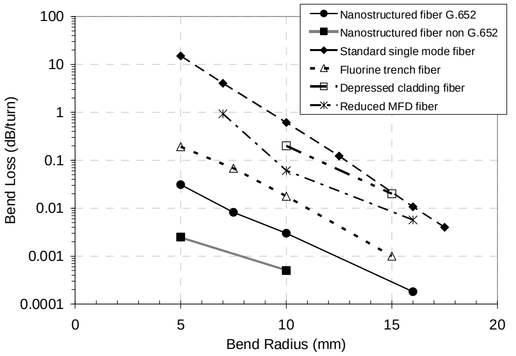

Figure 4. Comparison of bending performance of nano-engineered fibers with standard single-mode fiber and trench fibers.

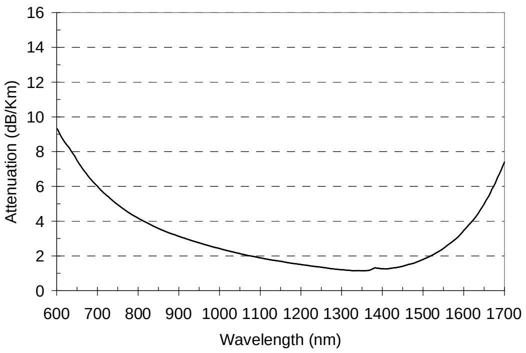

Figure 5. Attenuation spectrum for a fiber with pure silica core and nano-engineered cladding

The second design shown in Figure 3 has a pure silica core and a nano-engineered cladding. This design does not require any conventional dopants in the core and the cladding regions. Both single-mode or multimode fibers can be designed by changing the core size and void fill fraction in the cladding. For single-mode designs, the wavelength dependent effective index property of nano-engineered cladding can be used to design a fiber with very wide single-mode operating window. As an example, Figure 5 shows a measured spectral attenuation of a fiber with a pure silica core and a nano-engineered cladding. The fiber is single moded over the complete measured wavelength range of 600 to 1700 nm.

4. Conclusions

We have reviewed the new nanoStructures technology for making nano-engineered fibers. The new technology is compatible with the OVD process and suitable for large scale production. The nano-engineered glass material exhibits several unique features that are interesting for designing fibers for different applications.

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