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Low scattering loss fiber with segmented-core and depressed inner cladding structure

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ABSTRACT

In this paper, using the FEM method new low-loss fiber is proposed to minimize Rayleigh scattering with a segmented-core and depressed inner-cladding. The optical loss of the designed fiber is calculated based on Rayleigh scattering losses. Rayleigh scattering loss (RSL) has been estimated by Rayleigh scattering coefficient (RSC) and power distribution in the fiber. We have shown loss of less than 0.3 dB/km at 1310 nm, 0.18 dB/km at 1550 nm for step-index fibers which consist of conventional glass compositions such as SiO_2, GeO_2–SiO_2, F–SiO_2 while satisfying all of ITU-G.652.D attributes.

1. Introduction

Low loss optical fibers with the pure silica core have been a strongly favored transmission medium enabling greater system reach and longer span lengths in long-hual and regional terrestrial networks [1,2]. Extended fiber reach is especially useful in constructing and planning new networks which must span difficult terrain. Loss reduction of the fibers especially near OH overtone band near 1380 nm has enabled various wavelength division multiplexed (WDM) systems along with appropriate optical amplifiers such as WDM over S, C, and L bands using erbium doped fiber amplifiers (EDFAs) [3–5]. Recently ultra-low loss (ULL) fiber has been developed to further reduce Rayleigh scattering loss (RSL) in the O and E bands by using a special glass material [6]. Yet, combination of conventional glass compositions such as SiO_2, GeO_2–SiO_2, and F–SiO_2 has not been fully investigated and it would be highly advantageous in actual fabrication processes if these conventional glasses could be used in ULL instead of specialty glasses. RSL depends on optical property of material, fiber parameters and fabrication process; however, it has been shown that the RSL increase which occurs due to drawing tension is small and it is not the main factor [7].

In this paper, we propose a new fiber design to reduce RSL with a segmented-core (SC) and depressed inner cladding (DIC) that consist of conventional glass compositions, SiO_2, GeO_2–SiO_2, F–SiO_2 while satisfying all the optical attributes required by ITU G.652.D standards for single mode fibers (SMFs). This fiber has the lowest loss of any terrestrial-grade fiber with the maximum attenuation available between 0.17 and 0.18 dB/km at 1550 nm. With this fiber long-hual networks are scalable for higher capacities. A thorough analysis of the proposed waveguide was performed using a vectorial finite element method (FEM) package and parametric studies of optical loss were carried-out in terms of RCL.

2. Fiber design and characteristics

2.1. Mode analysis methodology

The electric fields of guided modes in step index fibers could be obtained by solving Maxwell's equations for the given boundary conditions. For the propagating modes along *z*-direction in the fiber, the transverse components are derived from the longitudinal component E_z.

Although analytical solutions exist for this simple structure, we have chosen to use the FEM because it can easily be adapted to include the directions in fabrication unavoidable in realistic structures.

FEM has been one of the most accurate methods to investigate the propagation properties of guided modes providing highly reliable estimates on modal characteristics such as effective refractive index, field distribution, and cutoff wavelength. In FEM, analysis of an optical waveguide starts from the scalar wave equation where the mode field function satisfies equation

$$\nabla^2\varphi + k_0^2\,[n^2(x,y) - n_{\text{eff}}^2]\varphi = 0 \quad (1)$$

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Subdividing the domain of interest into triangular meshes, a set of matrix equations is obtained applying the variation principle, and the eigenvalues of the equation could be solved for the given boundary conditions using FEM.

2.2. Fiber losses

The total optical loss in silica glass fibers consists of the following contributions: α_R Rayleigh scattering loss (RSL), α_{IR} infrared absorption loss, α_{OH} the OH bond absorption loss, α_{UV} ultraviolet absorption loss, α_{IM} imperfection loss between core and cladding, and α_{im} absorption loss of other impurities [7]. The spectral loss in optical fiber is expressed as

$$\alpha = \alpha_R + \alpha_{IR} + \alpha_{OH} + \alpha_{UV} + \alpha_{IM} + \alpha_{im} \tag{2}$$

With the advancement of fiber fabrication techniques, it has become possible to reduce optical losses [8]. α_{OH} has been significantly reduced by dehydration processes [9]. With the present state of art fabrication techniques, α_{IM} is almost negligible. The viscosity-matching technique has been suggested to reduce additional imperfection loss, which took advantage of the dopants GeO_2 and fluorine (F) to match the core and cladding viscosity [10,11]. α_{im} is also negligible and α_{UV} can be also ignored in O and E bands. Therefore, a model for estimating the optical loss of fibers can be expressed as total loss α_T with a sufficient accuracy as the sum of α_R and α_{IR}.

$$\alpha_T = \alpha_R + \alpha_{IR} \tag{3}$$

The infrared absorption loss is given by

$$\alpha_{IR} = C\exp\left(-\frac{D}{\lambda}\right) \tag{4}$$

where coefficients C and D are dependent on materials. In calculation, the absorption loss coefficients C and D are assumed to be 6.65×10^{12} dB/km, and 52.62 μm, respectively [7]. They are also assumed to be independent of the amount of dopant.

RSL is responsible for the majority of fiber loss in the O and E band as well as in C band [7,12–16]. It strongly depends on the fiber materials and the index profiles. Different types of fiber have different dependencies on those parameters because of the different optical power confinement factors in every layer.

RSL is given by the overlap integral between the light intensity $P(r)$ and Rayleigh scattering coefficient (RSC) $A(r)$ across the fiber cross section as

$$\alpha_R = \frac{1}{\lambda^4}\frac{\int A(r)P(r)\,rdr}{\int P(r)rdr} \tag{5}$$

Which is known as Rayleigh's inverse fourth-power law [7].

RSL can be expressed as the summation of RSC due to concentration fluctuation A_c and density fluctuation A_d. While A_c is independent of thermal treatment of silica-based glasses during fiber drawing, A_d changes depending on fictive temperature T_f in doped glasses as well as pure silica glass. It is possible to control A_d by changing their T_f values through drawing fibers slowly at lower temperatures. This method is applicable to various types of silica-based optical fiber [13]. Therefore, in the calculation of RSL we just consider the effect of concentration fluctuation which increases with increasing dopant added to the silica.

2.3. Rayleigh scattering coefficient

The RSC linearly depends on the relative-index difference (Δ) generated by doping silica with GeO_2 and F.

$$\begin{aligned} A &= A_0(1+0.41\Delta)\ for\ \text{F}-doped\ glass \\ A &= A_0(1+0.44\Delta)\ \text{for GeO}_2-\text{doped glass} \end{aligned} \tag{6}$$

where A_0 is the RSC of pure silica glass and Δ is normalized index difference associated with the GeO_2 and F doping. These formulas clearly show that silica doped with germanium and fluorine has an elevated RSC relative to that of pure silica, resulting in excess scattering loss. The RSC increases as the dopant increases and the dependence is the same for F-doped and GeO_2-doped glasses. The reason is that concentration fluctuation increases with increasing dopant added to the silica. For F-doped fibers, the refractive index decreases as the dopant of F increases while the refractive index of GeO_2-doped glasses increases as the GeO_2 concentration increases.

2.4. Waveguide parameters

In this section, we introduced the two different types of designed fiber with SC and DIC; Type 1 fiber with a highest refractive index at the central core and Type 2 fiber with a low refractive index at the central core.

The waveguide structure of the proposed fiber with SC and DIC is schematically shown in Fig.1(a). Refractive-index profiles of the fiber Types 1 and 2 are shown in Fig.1(b) and (c) respectively. The geometrical dimensions and relative index differences are summarized in Table 1 for two types of ULL fiber.

Table 1
Waveguide parameters of Types 1 and 2 fibers with SC and DIC.

	a_1 (μm)	Δn_1 (%)	a_2 (μm)	Δn_2 (%)	a_3 (μm)	Δn_3 (%)	a_4 (μm)	Δn_4 (%)
Type 1	2.5	0.37	4.2	0.2	6	0	30	−0.10
Type 2	1.5	0	4.2	0.2	6	0	30	−0.10

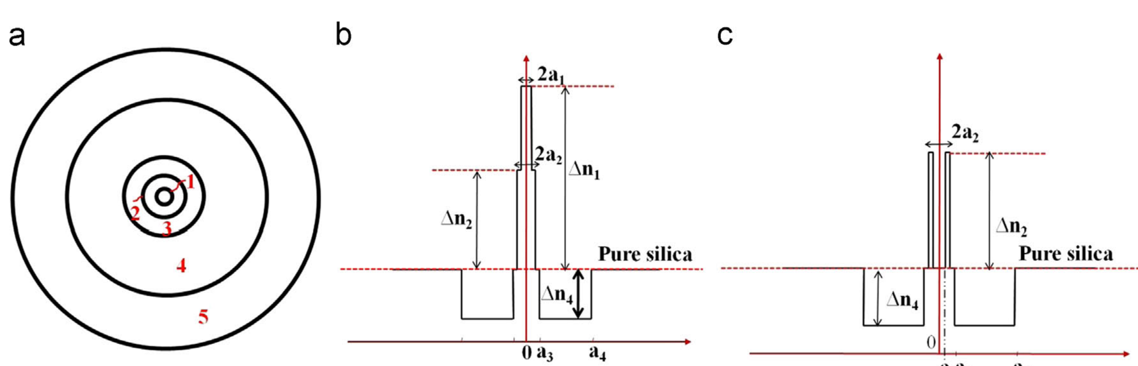

Fig. 1. (a) Cross-section of the proposed optical fiber. Refractive index profile of fiber (b) Type 1, and (c) Type 2.