Quasi Single-Mode Fiber With Record-Low Attenuation of 0.1400 dB/km

R. Khrapko, S. L. Logunov, M. Li, *Fellow, IEEE*, H. B. Matthews, P. Tandon, and C. Zhou

***Abstract*— We report a quasi single-mode fiber setting an absolute low attenuation record of 0.1400 dB/km at 1560 nm or 0.1407 at 1550 nm. The fiber core is silica-based, doped with halides (Cl, F) and an alkali oxide (K_2O). This core composition, along with the improved profile design, glass making and draw process conditions, provides an exceptionally low Rayleigh scattering coefficient and small angle scattering loss. The record low loss was achieved in a fiber with higher mode field confinement in the core and reduced intensity at the core-clad interface and in the cladding.**

***Index Terms*— Fiber optics, optical fiber losses, optical-fiber networks.**

I. INTRODUCTION

ATTENUATION reduction in optical fibers has been the prime goal of research institutions and businesses since the first low-loss optical fiber was developed in 1970, making fibers a practical communication medium [1]. That fiber had a silica core doped with TiO_2 and pure silica cladding. A big step in attenuation reduction was made when TiO_2 dopant in the core was replaced with GeO_2 [2]. Yet another attenuation improvement was achieved with pure silica core having a high level of chlorine, and low refractive index cladding doped with fluorine [3]. In 2002, two record results with low attenuation fibers, at 0.151 dB/km and 0.1484 dB/km, were reported [4], [5].

In parallel, pure silica-core fibers doped with alkali metals were developed, which helped to reduce fictive temperature and Rayleigh scattering in the fiber [6], [7], [8]. Single-mode fibers made using these new core compositions surpassed the previously set attenuation records and achieved a minimum attenuation of 0.1460 dB/km in commercially available fiber [9]. Most recently, a new attenuation record of 0.1419 dB/km was reported in 2017 [10].

Two other approaches to making the lowest attenuation fiber have been explored: oxide-free solid-core fibers for deep infrared transmission, and hollow-core fibers (HCF). Neither have yet achieved the losses of silica-core fibers, although a recent development of hollow-core fiber based on Double-Nested Antiresonant Nodeless Fiber (DNANF) [11] produced a sample with 0.174 dB/km [12], and the feasibility of <0.1 dB/km is being discussed [13], [14]. Still, significant ecosystem developments in long lengths, cabling and connectivity are needed for HCF to be competitive with conventional silica-core fibers.

Efforts continue to improve the characteristics of optical fibers in transmission systems and mitigate non-linear impairments. In many fiber products designed for long haul and submarine applications, low attenuation was combined with large effective area of up to 150 μm^2, which is the current limitation for single-mode fiber designs. To increase further the effective area, quasi single-mode fiber (QSMF) designs have been proposed [15]. Effective area of 200-220 μm^2 and fiber attenuation of 0.157 dB/km have been demonstrated. High-speed transmission with high spectral efficiency has been reported. To further increase system reach and improve system performance, lower attenuation is desired.

We here disclose a novel QSMF approach for reducing losses in alkali-doped, silica-core optical fibers to record-low attenuation of 0.1400 dB/km at 1560 nm and 0.1407 dB/km at 1550 nm. The fibers disclosed here have the potential to be used in practical commercial systems using fundamental mode launch and multi-path interference (MPI) compensation.

II. NOVEL QSMF APPROACH FOR REDUCING FIBER ATTENUATION

In this work, building on our advanced glass composition and draw processing, we have improved a QSMF design that achieves ultra-low attenuation by reducing losses of the fundamental mode due to Rayleigh scattering, absorption, and Small Angle Scattering (SAS). The fiber refractive index design is shown schematically in Fig. 1a. The fiber consists of a core, an inner cladding, and an outer cladding. The fiber core is potassium-doped silica with low concentrations of chlorine and fluorine. The inner cladding is doped with fluorine to lower the refractive index to define the core. The outer cladding is fluorine doped to a lower level than the inner clad to create a depressed inner cladding structure, which offers flexibility in controlling fiber cutoff wavelength and reducing fiber bending loss. The specific QSMF design which made the record low attenuation fiber is achieved by increasing fiber core diameter to 19 μm. Fiber 2 in Fig. 1a illustrates Vascade EX2000® refractive index profile (not exact), and the transformation from fiber 2 to fiber 3 shows exactly how our QSMF profile was achieved: radial scaling of the core and

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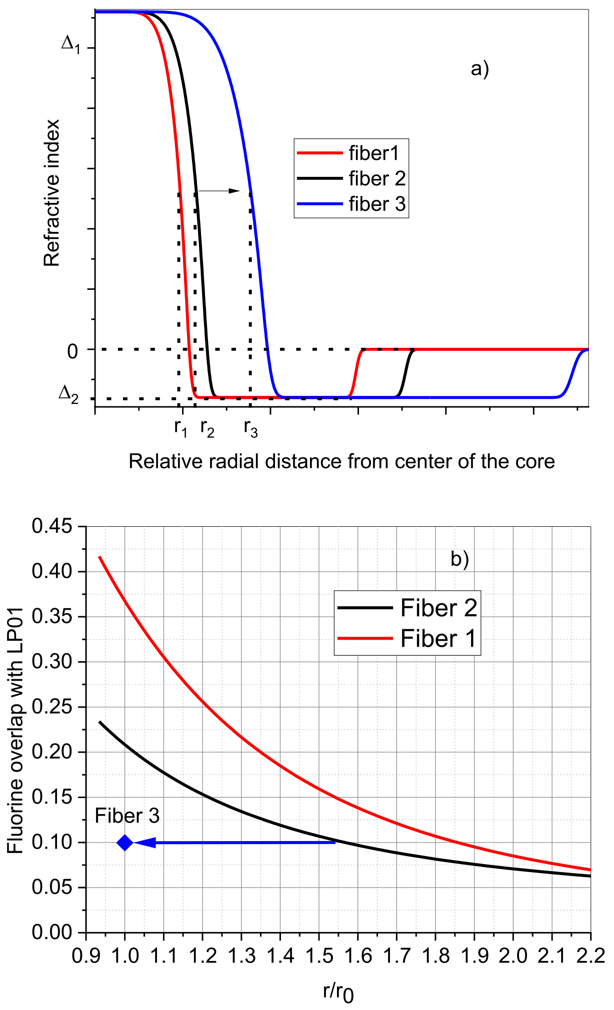

Fig. 1. Refractive index profiles for the fibers used in the study: r_1, r_2, r_3 are the radii of the cores for fiber 1, fiber 2, fiber 3 (a) and modeling result for overlap of LP01 mode with fluorine concentration as a function of core radius relative to starting profile (b).

inner clad by a factor of 1.55. The mode-field diameter (MFD) increases by a factor of 1.18 (from 12.0 μm to 14.2 μm) with this transformation. Fiber 1 was added as a comparative example representative of our fiber for terrestrial applications, having cable cutoff wavelength below 1260 nm and mode field diameter of 10.5 ± 0.5 μm.

Attenuation in single-mode optical fibers is dominated by the Rayleigh scattering component, which originates from the density fluctuations driven by fictive temperature of the glass, and from the concentration fluctuations of dopants in both the core and the cladding. Rayleigh scattering coefficient, R, can be presented as [16]:

$$R = R_d + R_c \tag{1}$$

where R_d represents Rayleigh scattering on density fluctuations and R_c represents Rayleigh scattering on dopant concentration fluctuations.

$$R_d = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K_B T_f \tag{2}$$

where λ is wavelength, n is refractive index, p is photo-elastic coefficient, β_c is isothermal compressibility, K_B is Boltzmann constant, T_f is fictive temperature. The only physically significant variable affecting scattering on density fluctuations is the fictive temperature, which is dramatically reduced by ~100 wt. ppm of alkali oxide dopant in the fiber core [6], [7], [8].

For small dopant concentrations, R_c is proportional to $x(dn/dx)^2$, where x is the mole fraction of the dopant in SiO_2-based glass and n is the refractive index of the glass.

In the core of potassium-doped pure silica-core (KPSC) fiber only density fluctuations play a significant role, as the concentrations of K_2O, fluorine and chlorine are very low. The density fluctuations in the core are moderated by lower fictive temperature resulting from potassium doping and are further reduced by annealing during the fiber draw process. This differs from the cladding, where higher fluorine dopant levels and the resulting concentration fluctuations add to the loss.

R_c in KPSC fiber is proportional to the overlap integral between LP01 mode and fluorine-induced Rayleigh concentration fluctuation component. This loss due to fluorine doping is described in [17] and [18]. Experimental data [17] shows that 4 mol% of fluorine increased Rayleigh scattering coefficient by 0.174 dB/km/μm^{-4} or 0.030 dB/km additional loss due 4 mol% fluorine. The cladding of our fibers has fluorine content in the range from 3 to 3.5 mol%, and the integral overlap with LP01 is from 10% for fiber 3 to 37% for fiber 1. This translates into additional loss due to R_c of 2.5-10 mdB/km.

Numerical modeling shows that the overlap integral is closely related to the core size of the fiber as shown in Fig. 1b. The overlap integral shown in Fig. 1b is defined as the normalized power multiplied by the relative fluorine concentration in the cladding region. The overlap decreases as the fiber core radius is scaled up from the nominal r_0 of fibers 1 and 2. Mode field diameter of LP01 mode increases much less than the core size. This resulted in a better confinement of the power in the low-loss core and reduced the power at and outside of the core/clad interface. Profile designs changing the relative refractive indices Δ_1 and Δ_2, and radius of the trench were not included in our low attenuation study.

A simple scaling up of the core size resulted in a QSMF fiber, as only the LP01 mode is launched. The LP11 mode is also a guided mode, having a higher loss.

In our experiments, attenuation was measured using 24 km fiber reels, and only a small fraction of launched power propagated in LP11 mode, either due to excitation at the launch, or distributed coupling from the fundamental mode along the fiber. In addition to the large-core fiber design for controlling confinement of fundamental mode in the core, glassmaking and draw conditions were also optimized to lower overall attenuation. This includes the choice of alkali and halide concentrations that balance glass devitrification risk and viscosity reduction of the core glass. Furthermore, the glassmaking process is improved to reduce concentrations of absorbing contaminants and glass defects. Draw conditions and processes, including the use of a slow cooling furnace, are designed to minimize fictive temperature (T_f in Eq. 2) and glass defect concentrations in the final fiber.

TABLE I

Fiber Cable Cutoff Wavelengths, Mode Field Diameters, and Loss Components at 1550 nm. Calculated B-Term (Unknown Loss) is a Difference Between Actual Loss and a Sum of Rayleigh Scattering, SAS, and IR Absorption Due to Silica Infrared Absorption Tail. It is Likely a Composition of Contaminants and Glass Defects Absorption, and Micro-Bending Losses

	Cutoff, nm Meas.	MFD, nm Meas.	R_c, dB/km Calc.	R total, dB/km Calc.	SAS, dB/km Meas.	IR loss, dB/km Fixed	B-term, dB/km Calc.	Loss, dB/km Meas.
fiber1	1230	10.5	0.0100	0.1350	0.0045	0.015	0.0019	0.1564
fiber2	1400	12.0	0.0055	0.1235	0.0025	0.015	0.0055	0.1465
fiber3	2400	14.2	0.0025	0.1200	0.0010	0.015	0.0047	0.1407
Ideal	-	-	0	0.1175	0	0.015	0	0.1325

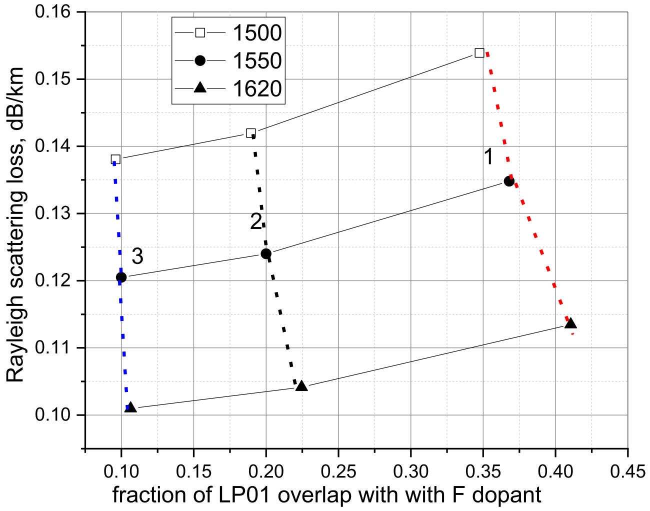

Fig. 2. Raleigh scattering loss change as a function of fraction of overlap integral with fluorine dopant for the three fiber designs.

III. Experimental Results and Discussion

To demonstrate the low attenuation approach discussed in the previous section, we made three fibers with three different designs. The design parameters were selected to have different cutoff wavelengths, effective areas and overlaps with fluorine. Fibers 1 and 2 are single-mode fibers with cable cutoff wavelengths below 1260 and 1500 nm respectively, while fiber 3 is QSMF with a cable cutoff wavelength of 2400 nm. The fibers have different effective areas ranging from 86.5 to 158.3 μm^2.

Using the measured refractive index profiles, we computed the overlap of LP01with fluorine for the three fibers. The results for fibers 1-3 show significant decrease of mode overlap with fluorine at any wavelength, though the effect is stronger at longer wavelengths where MFD is increased. These calculations for fluorine dopant allowed us to obtain the concentration fluctuation part of Rayleigh scattering, R_c, for each fiber type shown in Table I.

R total is measured using cutback method at wavelengths below 1000 nm where attenuation components other than scattering are negligible, or $\mathrm{R_d}$ is determined using Raman spectroscopy in transmission Raman at 1060 nm, as described in [19]. R total at 1550 nm is obtained via extrapolation by wavelength, using λ and n power laws from Eq. (2). R_c component is extrapolated separately to account for changing overlap integral with fluorine, and then recombined into R total at 1550 nm using Eq. (1).

The Rayleigh scattering coefficients for the three fibers at 1550 nm are listed in Table I. We also calculated the overlap integral for each fiber and examined its correlation to the Rayleigh scattering coefficient. Fig. 2 shows the Rayleigh scattering losses for each fiber as a function of fraction of the overlap integral of LP01 with fluorine dopant at three wavelengths of 1500, 1550 and 1620 nm. The three dashed lines represent the three different profile designs.

Smaller overlap with fluorine results in lower Rayleigh scattering loss. An added benefit of the larger core diameter is reduced SAS loss as there is a reduced power overlap at the core/clad boundary, where viscosity differences drive micro-deformations of the core diameter. We believe that the reduction of optical power at the core/clad interface with increasing core size and higher mode confinement inside the core explains the trend of SAS measured in fibers 1, 2, 3 in Table I. We measured SAS by the method described in [20].

Spectral attenuations for the fibers were measured using a spectral cutback technique compliant to the IEC 60793-1-40 standard [9]. Measured total loss at 1550 nm is shown in Table I, that is an average of three measurements with standard deviation of 0.2 mdB/km. The loss spectrum for the QSMF fiber 3 is plotted in Fig. 3. The lowest attenuation values measured in a 24 km reel of fiber are 0.1400 dB/km at 1560 nm and 0.1407 dB/km at 1550 nm. While the input power was launched in LP01 mode, we assume that a small portion of it was coupled into a higher loss LP11 along the 24 km length, thus increasing the attenuation. When this reel of fiber was cut in the middle and the half-lengths measured separately, they both had lower attenuation, averaging 0.1395 dB/km at 1560 nm, the lowest net fiber attenuation reported to date. This indicates that a very small portion of the input power was coupled into higher order mode over the 24 km length, while QSMF attenuation may be further reduced if such mode coupling is mitigated.

As shown in Table I, if the overlap of the LP01 mode with fluorine is set to 0, the minimum attenuation is projected to be 0.1325 dB/km. This assumes no absorbing impurities or defects and negligible small angle scattering loss. This provides an approximate attenuation limit for silica-based fiber given our draw conditions and natural-isotope mixtures of oxygen and silicon. Using heavier isotopes may further reduce IR absorption.

Fibers with QSMF designs have cable cutoffs that can be substantially higher than the nominal, C-band operating wavelength of 1550 nm. However, the ultra-low attenuation of these fibers is still potentially attractive for commercial transmission systems if the optical signal is launched exclusively into the fundamental mode. The advantages of such QSMF fibers for telecommunication systems include lower loss due to Rayleigh scattering, SAS reduction, and possible large effective area.

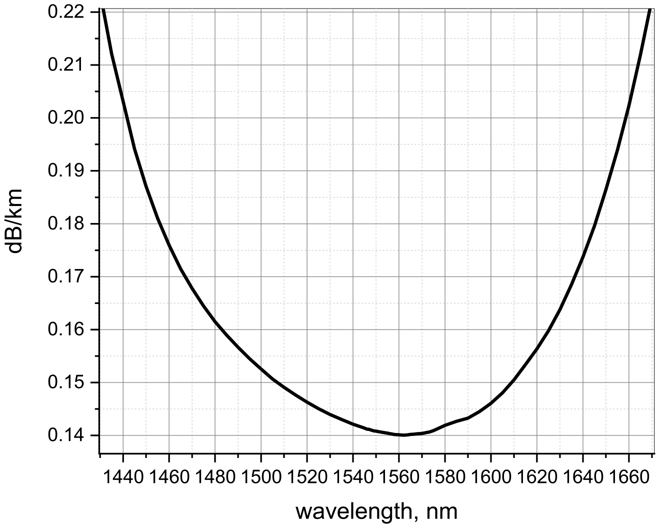

Fig. 3. Spectral attenuation for the record fiber 3.

In our fiber, power coupling to LP11 mode did not significantly increase attenuation. However, such mode coupling resulting in MPI would need to be further addressed. Multi-path interference (MPI) results in transmission impairment, primarily due to differences in mode group velocities. MPI impairment can be addressed by choosing appropriate QSMF fiber designs in combination with MPI compensation strategies. This is beyond the scope of the current contribution and would be an area of our future explorations.

IV. Conclusion

We have used a novel QSMF approach to achieve record-low attenuation of 0.1400 dB/km at 1560 nm and 0.1407 dB/km at 1550 nm in alkali-doped, silica-core fibers. The ultra-low attenuation was obtained via improvement of a large core fiber design, combined with low-loss core construction, and draw conditions. Rayleigh scattering can be further reduced by draw conditions that allow for increased glass relaxation, and by changing alkali doping level. LP01 mode losses can also be lowered by reducing potential coupling between fundamental and higher loss, higher order modes. Future work will consider large-core profiles that minimize multi-path interference (MPI).

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