Ultimate Limits of Effective Area and Attenuation for High Data Rate Fibers

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Abstract: High data rate telecommunication networks operating at 100 Gb/s require low loss fibers with very large effective areas to mitigate nonlinearities. The state of the art fiber technologies needed to achieve this balance are discussed.

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

1. Introduction

Recent years have seen a steady growth in both the deployed lengths and capacities of optical fiber telecommunication systems. Figure 1 illustrates that after the burst of the telecom bubble in 2001-2002, the fiber volume was flat for several years before rebounding primarily due to the growth of access networks. At the same time, new systems developed for the installed fiber base have enabled a tremendous increase in the bit rate-reach product, as shown in Figure 2. This growth has led the telecommunications industry back on a capacity quest, with an emphasis of supporting access-driven markets and providing long-haul capability for emerging markets.

Systems operating at 40 and 100 Gb/s using coherent detection have also recently become commercially available and have produced record single fiber capacities and spectral efficiencies. However, due to the sensitivity of these types of systems to nonlinearities, fibers with very large effective areas (Aeff) are needed to optimize their performance. At the same time, there is a continued need for low attenuation to achieve the highest possible optical signal to noise ratio (OSNR). This paper will discuss the fiber technologies that achieve this balance.

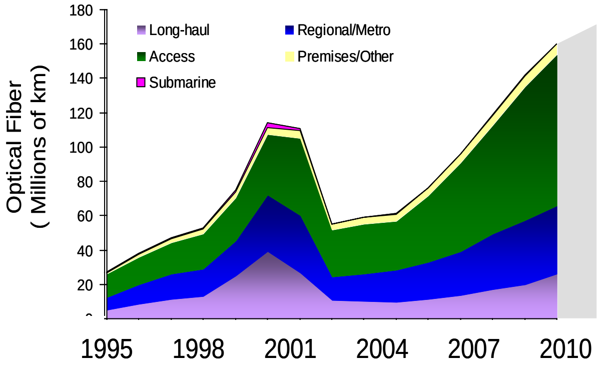

Figure 1. Annual deployment of fiber from 1995 to present.

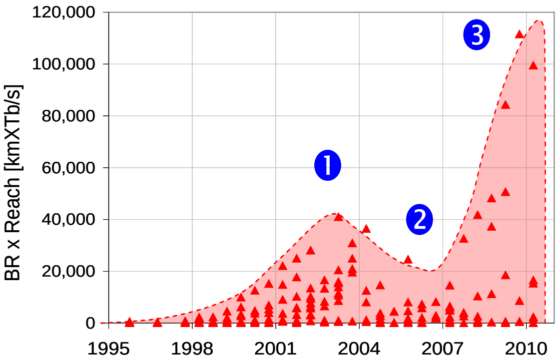

Figure 2. Product of bit rate and reach from 1995 to present

2. Fiber Design

An important consideration in evaluating the fiber design space is that the glass and coating of the optical fiber are highly coupled components in a composite system. Figure 3 shows a schematic of this system, where the glass includes a core and a cladding, and the coating is typically has an inner primary coating that forms a soft cushioning layer and an outer primary coating that protects against abrasions and punctures. The softness or hardness of the coating layers is determined by their elastic moduli, which are typically less than ~1 MPa in the inner primary and greater than ~100 MPa in the outer primary coating.

The optical properties determined by the glass design include the Aeff, cutoff wavelength and macrobending resistance. The relationship between these attributes can be understood by considering a simple step index design, which is shown schematically in Fig. 3. The cutoff wavelength has an upper limit below the minimum wavelength of the application window, e.g. 1530 nm for a G.654.B cabled fiber, while the macrobend sensitivity usually has a specified upper limit, e.g. less than 0.5 dB for 100 turns at a bend radius of 37.5 mm. For a step index design, the maximum effective area that can be achieved given the cutoff and macrobend ceilings is approximately 110 µm^2 [1].

While an Aeff of 110 µm^2 may provide acceptable performance in systems operating at 10 or even 40 Gb/s, even larger effective areas are desirable for systems operating at higher bit rates with coherent detection [2]. Adding features such as a depressed cladding or a trench, as shown schematically in Fig. 3, can suppress *macro*bending losses in G.657 fibers and are also beneficial in the cutoff-shifted G.654 fibers. However without any modification of the fiber-coating system, it has been reported that the effective area can only be increased to approximately 120 µm^2 before microbending losses become the limiting factor [3].

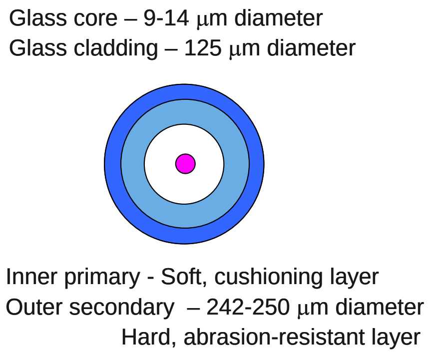

Figure 3. Fiber system with a core, cladding, inner primary coating and outer primary coating.

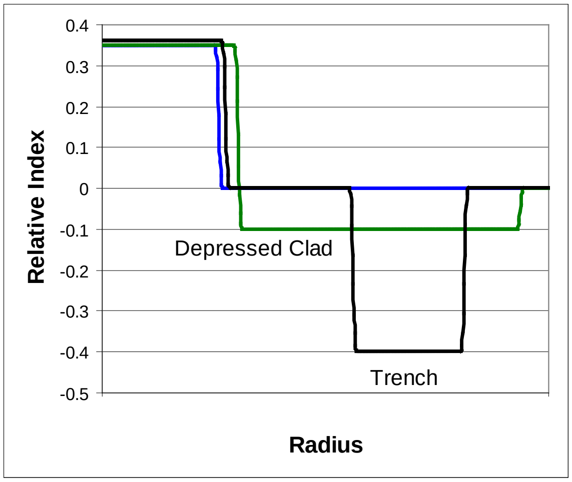

Figure 4. Step index, depressed-clad and trench fiber designs.

3. Microbending

Microbending is an attenuation increase caused by high frequency longitudinal perturbations to the waveguide. These perturbations couple power among modes in the fiber, and in the case of single-mode fiber, couple power from the guided fundamental mode (LP$_{01}$) to higher-order modes that are lost to the outer medium [4]. Given this description, it is easy to understand at least qualitatively why making the inner primary coating softer will help cushion the glass from external perturbations and hence improve the microbending performance.

A phenomenological model introduced by Olshansky captures the importance of treating the glass and coating as a composite system by predicting that the microbending losses scale with

$$\gamma_{micro} \propto \frac{a^4}{b^6 \Delta^3} E^{3/2}, \qquad (1)$$

where *a* is the core radius, *b* is the cladding radius, *Δ* is the relative refractive index of the core and *E* is the elastic modulus of the (inner primary) coating layer that surrounds the glass. Increasing the cladding radius will have the largest theoretical impact on the microbending response, but this parameter is constrained to 62.5 µm by most telecommunication standards. The relationship between *a* and *Δ* determines the cutoff wavelength, which is constrained by standards and functionality reasons, so these variables are not completely independent and together do not offer a significant lever for reducing microbending sensitivity. This leaves the inner primary modulus as a key factor for addressing the increased microbend sensitivity in large effective fibers.

We have experimentally verified the role of the inner primary modulus in mitigation of microbending by drawing a low loss blank with two coatings which have inner primary moduli of approximately 0.13 and 0.43 (Coating A and B, respectively). The effective areas of the fibers are ~139 µm^2, the cutoff wavelengths are similar, but the shipping spool attenuations at 1550 nm are 0.166 and 0.195 dB/km, respectively. Figure 5 shows the microbend response as characterized using IEC-TR62221 Method C wire mesh drum test. Commercial fibers typically exhibit less than 1 dB/km attenuation increase using this test. It is evident that to derive the benefits of ultra-low attenuation, a fiber with very large effective area requires a coating with an optimized inner primary modulus to protect against microbending.

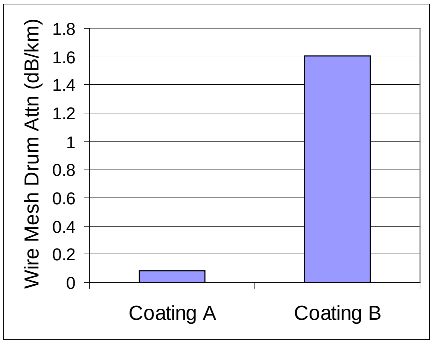

Figure 5. Wire mesh microbend attenuation for two different coatings.

Fiber Type	n2 (m2/W)	Aeff (sq. microns)	Attenuation (dB/km)	OSNR (dB)
Ge-Doped	2.3	82	0.19	-2.00
Ge-Doped	2.25	120	0.185	0.00
Silica Core	2.1	120	0.185	0.30
Silica Core	2.1	112	0.162	1.15
Silica Core	2.1	135	0.162	1.96
Silica Core	2.1	149	0.157	2.64

Figure 6. OSNR values for different combinations of the nonlinear index n_2, the effective area and the attenuation for a 50 km span.

4. Attenuation and Figure of Merit

Section 3 focused on the need for advanced coatings to reduce microbending sensitivity and enable the effective area to be increased to at least 140 μm^2. Another important attribute is the intrinsic attenuation of the fiber, which is largely determined by the glass composition, but is also impacted by the stress profile and drawing conditions [5]. A detailed discussion is beyond the scope of this paper; however it is insightful to look at the tradeoff between effective area and attenuation using an OSNR metric that compares the performance for two different single fiber spans [6]:

$$OSNR(dB) = 10\log(\frac{A_{eff,1}n_{2,2}}{A_{eff,2}n_{2,1}}) - (\alpha_1 - \alpha_2)\,L(dB), \qquad (2)$$

where the nonlinear index n_2 absent in the original derivation has been included. The subscript 1 refers to the fiber attributes being evaluated, while the subscript 2 is a reference fiber, which here has a Ge-doped core, an attenuation of 0.185 dB/km and an Aeff of 120 μm^2. The table in Figure 6 illustrates that, for a 50 km span, the reference fiber has an OSNR that is 0.3 lower than a fiber with a silica core due to the higher nonlinear index. Decreasing the attenuation to a level that is attainable in current ultra low loss fibers increases the relative OSNR by more than 1 dB, and the prototype fiber with the properties given in the last row of the table has an OSNR which is 2.6 dB higher than the reference fiber according to the simplified metric given by Eq. (2).

4. Conclusions

Fibers being developed for next generation high data rate systems are extending the boundaries of low attenuation and large effective area well beyond the realm of conventional commercial products. Ultra low loss fibers are routinely delivering attenuation values less than 0.17 dB/km, while co-optimization of the glass design and coating properties is enabling effective areas greater than 140 μm^2 with exceptional microbending and macrobending performance.

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