Bandwidth enhancement by differential mode attenuation in multimode photonic crystal Bragg fibers

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In multimode bandgap guiding fibers higher-order modes have high radiation losses. Once excited, after a short propagation distance such modes are leaked out of the fiber core. Reduction of the number of excited modes in the fiber core leads to a decrease of intermodal dispersion and a dramatic enhancement of fiber bandwidth. Due to the increase in the propagation loss, bandwidth enhancement by differential mode attenuation also leads to the reduction of the maximal length of a usable fiber span. We demonstrate that by proper design of a photonic crystal reflector long fiber spans of high bandwidth are possible.

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Large core diameter multimode optical fibers have been thoroughly investigated in view of their short length telecommunication applications.[1–4] Multimode plastic optical fibers, in particular, offer a cost-effective solution for applications in the automotive, avionics, and IT sectors.

The key parameter of a multimode fiber is its bandwidth. Measured in MHz·km, it characterizes the maximal transmission rate over a fiber span of 1 km. The principal factor limiting multimode fiber bandwidth is intermodal dispersion.[5] As every core mode is propagating with a somewhat different group velocity, a pulse launched into a set of fiber modes will exhibit temporal broadening increasing with propagation length. A train of pulses of a given bitrate is scrambled when temporally separated pulses start to overlap considerably, thus limiting the maximal bitrate. Generally, maximal bitrate reduces with the length of a fiber span.

Several strategies have been developed to decrease pulse spreading and increase bandwidth of multimode fibers. One strategy uses direct reduction of intermodal dispersion by design of the fiber refractive index profile. It was demonstrated that in graded index (GI) fibers[6–8] variation in the group velocities of individual modes can be considerably reduced. Another strategy of bandwidth enhancement proposes improving launching conditions[9] so that the pulse is launched into only a small subset of fiber modes with similar group velocities, thus effectively reducing intermodal dispersion.

In this Letter we present a differential mode attenuation mechanism of reduction of the intermodal dispersion through modal loss differentiation by the bandgap of a photonic crystal fiber. As will be seen from our discussion, this bandwidth enhancement mechanism can be easily implemented to enhance performance of the already existing solutions such as GI refractive index profile fibers. This theoretical work is also motivated by our recent experimental success in the fabrication of solid-core polymethyl methylacrylate (PMMA)/polystyrene (PS) Bragg fibers[10] (Fig. 1) for applications in the visible and near IR.

The concept of fiber bandwidth is convenient to introduce by first studying broadening of a Gaussian pulse due to the effects of individual mode and intermodal dispersions. Assuming pulse intensity at the fiber input $z=0$ as $I(t,0)=2/\sqrt{\pi}\exp(-(2t/\tau_o)^2)$, evolution of the electromagnetic field in a fiber can be written as

$$|F\rangle = \sum_j \sqrt{P_j^0} \int \mathrm{d}w |F\rangle_j \exp(i\beta_j(\omega)z - i\omega t) f(\omega), \quad (1)$$

where the sum is over the modal index j, $|F\rangle_j$ is a field of mode j normalized to 1 [W] of power, P_j^0 is a relative power in the mode j at the fiber input, and $I(t) = \int \mathrm{d}w \exp(i\omega t) f^2(\omega+\omega_0)$, where ω_0 is a carrier frequency. After propagation over a distance z, the temporal distribution of the pulse intensity can be calculated as $I(z,t)=\langle F|F\rangle$ by employing orthogonality of the normalized fiber modes $\langle F_i|F_j\rangle = 1[W]\delta_{i,j}$ and assuming that modal fields do not change substantially near ω_0.

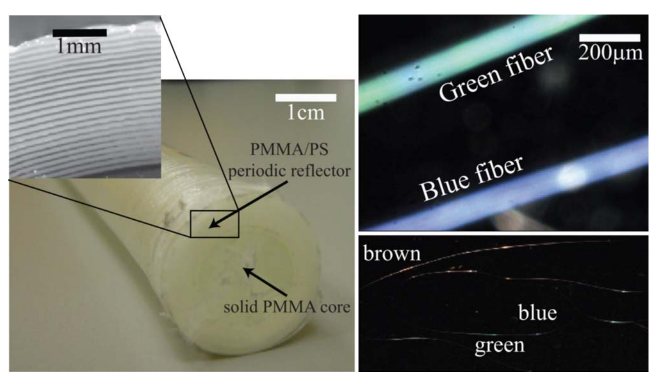

Fig. 1. (Color online) Solid-core photonic crystal Bragg preform and drawn fibers. The center wavelength of a reflector bandgap can be chosen anywhere in the visible, manifesting itself in the specific color of a drawn fiber.

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In the vicinity of a carrier frequency ω_0, we use Taylor expansion to describe the frequency dependence of the modal propagation constants:

$$\beta_j(\omega_0 + \Delta\omega) = \mathrm{Re}(\beta_j^0) + \frac{\Delta\omega}{v_i^g} + \frac{(\Delta\omega)^2 D_i}{2} + i\frac{\alpha_i}{2}, \quad (2)$$

where $\beta_j^0 = \beta_j(\omega_0)$, $v_j^g = (\partial\beta_i/\partial\omega)^{-1}$ is a modal group velocity, $D_i = \partial^2\beta_i/\partial\omega^2$ is a modal dispersion parameter, and $\alpha_j = 2\,\mathrm{Im}(\beta_i^0)$ is a modal attenuation coefficient that we consider frequency independent.

Pulse width $\tau(z)$ after propagation over a fiber length z can be found by calculating the proper time averages:

$$\langle \tau^2(z)\rangle = \langle F|t^2|F\rangle/\langle F|F\rangle - (\langle F|t|F\rangle/\langle F|F\rangle)^2. \quad (3)$$

After substitution of Eq. (2) into Eq. (1), evaluation of Eq. (3) gives

$$\langle \tau^2(z)\rangle = \frac{\tau_0^2}{8} + z^2\left([\langle v_g^{-2}\rangle - \langle v_g^{-1}\rangle^2] + 2\frac{\langle D^2\rangle}{\tau_0^2}\right), \quad (4)$$

where the average of a modal property M is defined as $\langle M\rangle = \Sigma_j(M_j P_j^0 \exp(-\alpha_j z))/\Sigma_i(P_j^0 \exp(-\alpha_j z))$.

To estimate the bandwidth of a fiber span of length z we consider a periodic pulse train with bitrate $B = 1/\tau_0$ of Gaussian pulses of width τ_0. According to Eq. (4), after propagating over distance z, individual pulses will broaden, $\tau(z) > \tau_0$, thus overlapping with the adjacent pulses. We consider the pulse train to be degraded when $\langle \tau(z)^2\rangle = 4\langle \tau(0)^2\rangle$. This criterion and Eq. (4) define the quadratic equation from which the maximal bitrate $B_{\max}(z) = 1/\tau_0$ and bandwidth $z \cdot B_{\max}(z)$ of a fiber span can be found. Typically, the effect of the individual mode dispersion is considerably smaller than the effect of intermodal dispersion. In this case expression for the bandwidth becomes independent of the fiber length:

$$z \cdot B_{\max}(z) = \sqrt{3/(8\langle \Delta v_g^{-2}\rangle)}, \quad (5)$$

where intermodal dispersion is $\langle \Delta v_g^{-2}\rangle = \langle v_g^{-2}\rangle - \langle v_g^{-1}\rangle^2$.

Note that power in a given mode decreases with propagation distance as $P_j(z) = P_j^0 \exp(-\alpha_j z)$. Thus, in a fiber where modal losses are strongly differentiated from one another, only the lowest loss modes will persist. This leads to the exponentially fast reduction of $\langle \Delta v_g^{-2}\rangle$ with fiber length, which is the key cause of bandwidth enhancement by differential mode attenuation. In what follows we demonstrate this mechanism by comparing the bandwidth of a step index (SI) total internal reflection (TIR) guiding fiber with that of a geometrically similar fiber having a photonic crystal reflector as a cladding.

In Fig. 2, for operational wavelength $\lambda_0 = 650$ nm we present modal propagation losses and corresponding group velocities of the core guided modes of the 120 μm diameter SI and solid-core Bragg fibers. Fiber modes were computed using a standard transfer matrix theory.[11] To simplify comparison with existing technologies, fiber core sizes and refractive index contrast were chosen to be similar to those of a Lucina

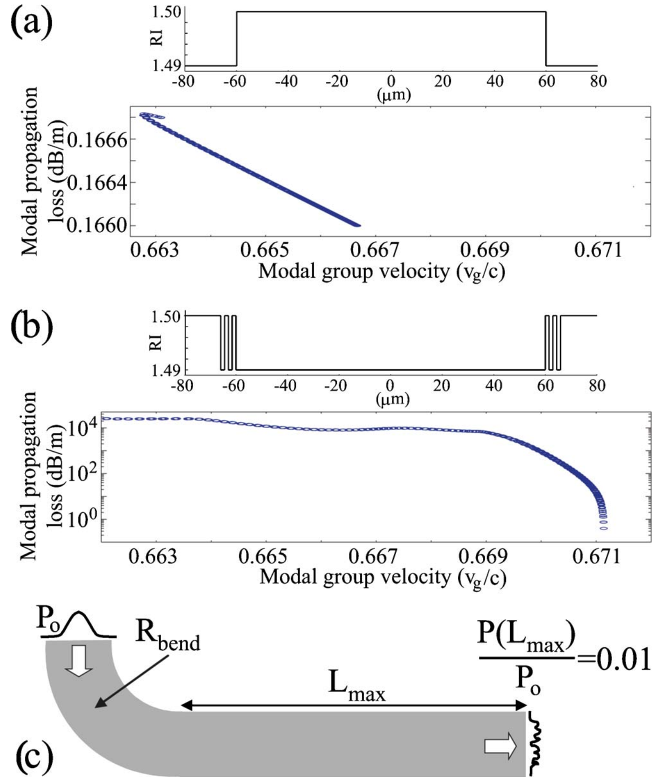

Fig. 2. (Color online) Modal propagation losses and corresponding group velocities of the core guided modes of the (a) SI-TIR fiber, (b) solid-core Bragg fiber with four reflector layers. Insets: fiber refractive index profiles. (c) Schematic of a fiber span including a bend and a straight section.

GI fiber with NA ~ 0.2. We further assume that both fibers are made of a PMMA polymer having 0.166 dB/m absorption loss. In a plastic SI fiber [Fig. 2(a)] $n_{\mathrm{core}} = 1.5$, $n_{\mathrm{clad}} = 1.49$, and all the modes have comparable losses similar to that of a PMMA polymer. Thus, once excited, all the modes will reach the fiber end with the same relative power, and no reduction of intermodal dispersion is expected. In our simulations we include all $\sim$800 modes with angular momentum $m = 0-10$. Bragg fiber [Fig. 2(b)] with $n_{\mathrm{core}} = 1.49$, $n_{\mathrm{clad}} = 1.5$ features a reflector of four 1.48 μm thick layers. In a bandgap guiding fiber only a small number of low-order modes with group velocities $\sim c/n_{\mathrm{core}}$ have relatively low radiation losses. Once excited, only those modes will survive at the end of a fiber span, thus reducing dramatically intermodal dispersion at the expense of the total transmitted power. In our simulations we consider all $\sim$1100 Bragg fiber modes with angular momentum $m = 0-10$, from which only 146 modes have radiation losses smaller than 100 dB/m. For both fibers, the absorption loss of PMMA material limits the fiber length to 120 m (20 dB loss over the fiber span).

To demonstrate bandwidth enhancement in a photonic crystal Bragg fiber compared with that of a SI-TIR fiber, we perform propagation simulation of a Gaussian pulse over a fiber span containing a macrobend Fig. 2(c). We employ coupled mode theory[12] to study bend-induced mode scattering. We assume that all the power at the fiber input is in a single Gaussian-like HE_{11} mode of a straight fiber.

The fiber mode is then launched directly into the 90° bend, which is followed by a straight fiber section of length $L_{\max}$. For bandwidth comparison $L_{\max}$ for both the Bragg and SI-TIR fiber spans is chosen to be the same and equal to that of a Bragg fiber span featuring 20 dB power loss at the end. In Fig. 3(a) the bandwidths of the Bragg and SI-TIR fibers are presented for various bend radii. For smaller bend radii (<30 cm) power coupling from the initial HE_{11} mode into the higher-order modes is especially pronounced. In a SI fiber, propagation through the bends of small radii leads to the excitation of a large number of high-order modes, thus increasing intermodal dispersion and reducing bandwidth. In contrast, the bandwidth of a Bragg fiber with a four-layer reflector remains approximately constant and a factor of ~30 larger than that of a SI fiber even for small bending radii. An increase in the Bragg fiber bandwidth comes through attenuation of all the higher-order modes with group velocities substantially different from c/n_{core}, thus dramatically reducing intermodal dispersion. A bandwidth increase via attenuation of higher-order modes comes with a price of shorter fiber spans, as seen from Fig. 3(b). Thus, the maximum length of a four-layer reflector Bragg fiber (assuming 20 dB loss) is limited to several meters.

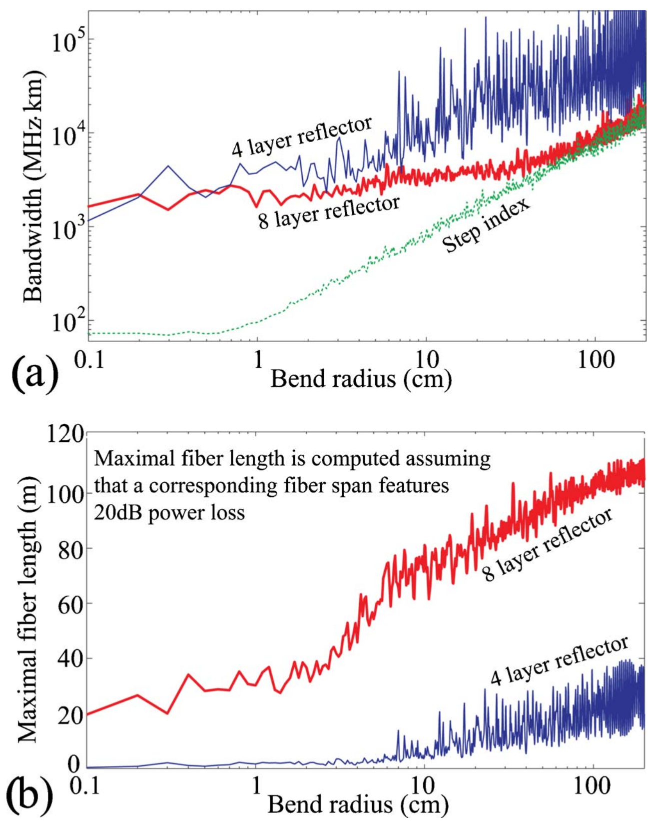

Fig. 3. (Color online) (a) Bandwidth comparison of the SI-TIR and photonic crystal Bragg fibers containing a macrobend of radius R_{bend}. Two Bragg fiber designs with four- and eight-layer reflectors are considered. At the bend input 100% power is in the Gaussian-like HE_{11} mode of a straight fiber. (b) Maximal length of a Bragg fiber span resulting in a total power loss of 20 dB.

By increasing the number of layers in a Bragg reflector, one can reduce modal radiation losses, thus increasing the length of a fiber span, while sacrificing somewhat fiber bandwidth. In Fig. 3 we also present bandwidth simulations for a Bragg fiber with an eight-layer reflector. In this fiber there are 211 modes with losses smaller than 100 dB/m, compared with 146 modes in a Bragg fiber with four-layer reflector. A greater number of low loss modes leads to the lower transmission loss, while at the same time increased intermodal dispersion. We note that a Bragg fiber with an eight-layer reflector still offers considerable bandwidth enhancement over that of a SI-TIR fiber, while allowing considerably longer fiber spans limited to a maximum of 120 m due to the fiber material absorption loss.

In conclusion, we demonstrated that bandwidth enhancement by differential mode attenuation is an inherent feature of multimode bandgap guiding fibers. By choosing a photonic crystal reflector of moderate efficiency so that the number of low loss modes is large enough for efficient power transfer, while not so large as to result in considerable intermode dispersion, long photonic crystal fiber spans of high bandwidth are possible.

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