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

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Abstract: In multimode bandgap guiding fibers higher order modes have high radiation losses. Thus, after a short propagation distance effective intermodal dispersion is reduced and bandwidth is dramatically enhanced compared to that of step index fibers.

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1. Introduction

Large core diameter multimode optical fibers have been thoroughly investigated in a view of short length telecommunication applications. Multimode plastic optical fibers, in particular, offer a cost effective solution for applications in automotive, avionics and IT sectors. The key parameter of a multimode fiber (MF) is the bandwidth. Measured in MHz*km it gives the maximal transmission rate over a fiber distance of 1km. Principal factor limiting MF bandwidth is an intermodal dispersion. As every core mode is propagating with somewhat different group velocity, then a pulse launched into a set of such modes will exhibit temporal broadening which will increase with propagation length. Typically, the effect of individual mode dispersion is negligible by comparison with that of an inter-modal dispersion, and broadening of a Gaussian pulse can be easily described. Thus, assuming pulse intensity at the fiber input as $I(t)=\exp(-2t^2/\tau_o^2)$, then pulse width $\tau(z)$ after propagation distance z can be expressed as [1]:

$$\tau^2(z)-\tau_0^2 = 8z^2\left(\left\langle v^{-2}\right\rangle - \left\langle v^{-1}\right\rangle^2\right)$$

$$\left\langle v^{-2}\right\rangle = \frac{1}{P(z)}\sum_i p_i(z)\left(v_i^g\right)^{-2};\ \left\langle v^{-1}\right\rangle = \frac{1}{P(z)}\sum_i p_i(z)\left(v_i^g\right)^{-1};\ P(z)=\sum_i p_i(z) \quad (1),$$

where the sums are over the modal index i, v^g_i is a modal group velocity, modal power after the propagation distance z is $p_i(z)=p^o_i\exp(-\alpha_i z)$, where α_i is a modal propagation loss and p^o_i is a power in the mode i at the fiber input.

Several strategies have been developed to decrease pulse spreading in a multimode fiber. One strategy is direct reduction of intermodal dispersion by design of fiber refractive index profile. It was demonstrated that in graded index fibers [2,3] spread in the group velocities of individual modes can be considerably reduced. Another strategy of bandwidth enhancement proposes improving launching conditions [4] so that the pulse is launched only into a small subset of fiber modes with similar group velocities, thus effectively reducing intermodal dispersion parameter.

Here we present differential mode attenuation mechanism of reduction of intermodal dispersion through modal loss differentiation by the bandgap of a photonic crystal fiber. This theoretical work is motivated by our recent experimental success in fabrication of the solid core Bragg fibers Fig. 1(a) for applications in the visible and near IR.

2. Bandwidth enhancement by modal loss differentiation in a solid core Bragg fiber

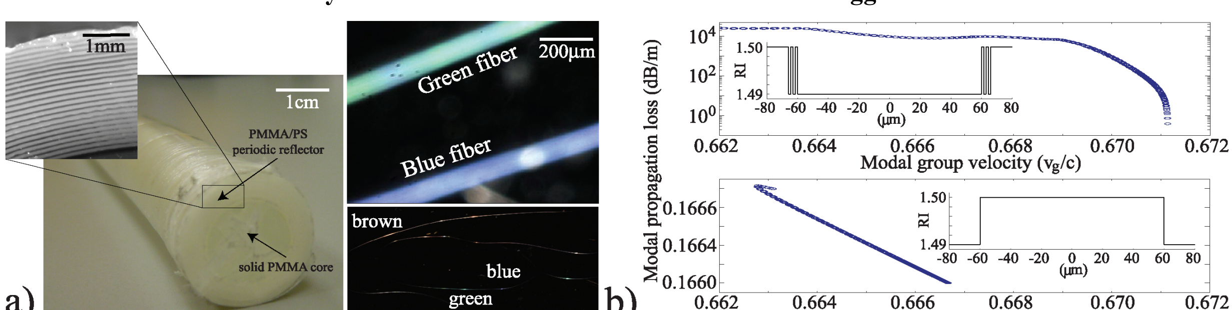


Fig. 1. a) Solid core photonic crystal Bragg preform and a drawn fiber. Center wavelength of a reflector bandgap can be chosen anywhere in the visible manifesting itself in the coloring of a drawn fiber. b) Modal propagation losses and corresponding group velocities of the core guided modes of the: (upper plot) solid core Bragg fiber, (lower plot) step index fiber. Insets: fiber refractive index profiles.

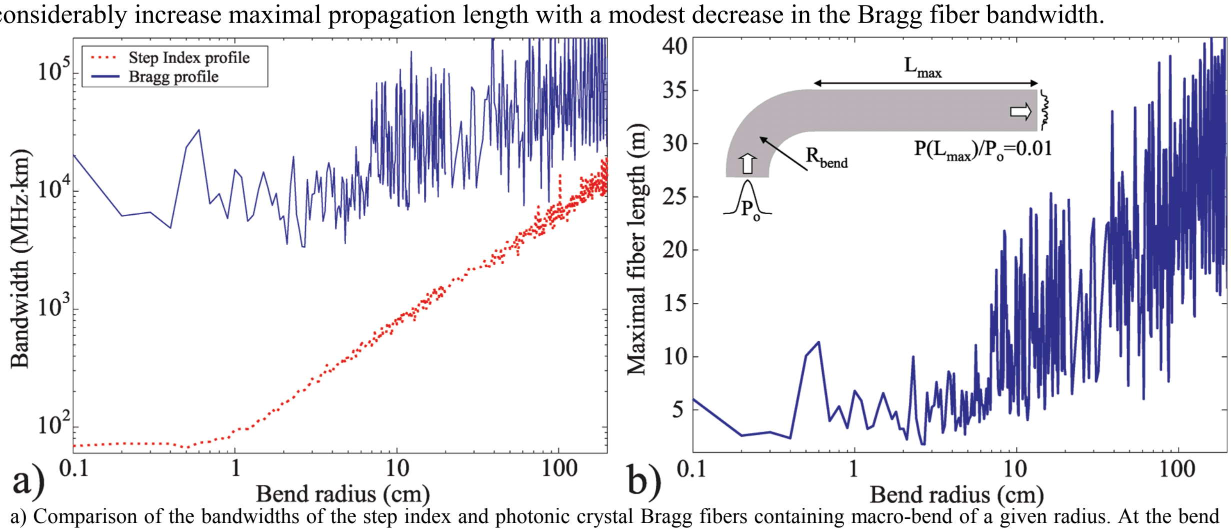
In Fig. 1(b) for a wavelength λ=650nm we present modal propagation losses and corresponding group velocities of the core guided modes of the 120μm diameter solid core Bragg fiber (upper plot), and a PMMA step index (SI) fiber (lower plot). In a SI fiber n_{core}=1.5, n_{clad}=1.49, all the modes have comparable losses due to 0.166dB/m bulk absorption of a PMMA polymer. Thus, once excited, all the modes will reach the fiber end with the same relative power. In our simulations we included all the ~800 modes with angular momentums m=0-10. Bragg fiber with n_{core}=1.49, n_{clad}=1.5 features a reflector of four 1.48μm thick layers. In a bandgap guiding fiber only a small number of low order modes with group velocities close to c/n_{core} feature relatively low radiation losses. Once excited, only these modes will survive at the end of a fiber span, thus reducing dramatically effective intermodal dispersion in expense of the total transmitted power. In our simulations we considered ~1100 Bragg fiber modes with angular momentums m=0-10, from which only 157 modes have radiation losses smaller than 100dB/m.

To estimate bandwidth of a fiber span of length *z* we imaging a periodic pulse train with bitrate $B=\tau_0^{-1}$of Gaussian pulses of width τ_0. According to Eq. (1) 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 $\tau(z)=2\tau_0$. This criterion and Eq. (1) define the maximal bitrate $B_{max}=1/\tau_0$ and bandwidth zB_{max} supported by the fiber span:

$$zB_{max} = \sqrt{3/\left[8\left(\left\langle v^{-2}\right\rangle - \left\langle v^{-1}\right\rangle^2\right)\right]} \quad (2).$$

To demonstrate bandwidth enhancement in a photonic crystal Bragg fiber compared to a SI fiber we perform propagation simulation of a Gaussian pulse over a fiber span containing macro-bend. We employ coupled mode theory [5] to study bend induced mode coupling. We assume that all the power at the fiber input is in the Gaussian-like HE_{11} mode of a straight fiber. The fiber mode is then launched directly into the 90^o bend which is followed by a straight fiber (inset Fig. 2 (b)). The total length of a fiber span for both Bragg and SI fibers is chosen to be the same and that of a Bragg fiber span featuring 20dB total loss at the end. In Fig. 2(a) bandwidths of the Bragg and SI fibers are presented for various bend radii. For smaller bend radii (<20cm) power coupling from the initial HE_{11} mode into the higher order modes is especially pronounced. In a SI fiber, propagation through the bend of small radius leads to the excitation of a large number of high order modes, thus increasing intermodal dispersion and reducing bandwidth.

In contrast, bandwidth of a Bragg fiber remains approximately constant and almost two orders of magnitude larger than that of a SI fiber even for small bending radii. 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. Bandwidth increase by attenuation of higher order modes comes with a price of shorter fiber spans as seen from Fig. 2(b). In fact by increasing the number of layers in the Bragg reflector one can considerably increase maximal propagation length with a modest decrease in the Bragg fiber bandwidth.



a) Comparison of the bandwidths of the step index and photonic crystal Bragg fibers containing macro-bend of a given radius. 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 (with a macro-bend) resulting in the total attenuation span loss of 20dB at the output end.

3. References

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