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Spectral Response of Bend Loss in Photonic-Crystal Fibers

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Abstract—Bend loss in photonic-crystal fibers (PCFs) has been investigated using the effective index method. Bend loss edges are observed for short wavelength as well as for long wavelength. It is observed that bend loss depends on the air hole size (*d*), normalized effective frequency (V_{eff}), and pitch (Λ) of a photonic-crystal fiber. Bend loss for different configurations of photonic-crystal fibers have been obtained, and it is shown that PCF can be designed for minimum bend loss for a broad spectral range.

1. INTRODUCTION

Photonic-crystal fibers (PCFs), a new class of optical fibers constituting a periodic array of air holes running down its length, have many unique features, such as single mode operation from the UV to IR spectral regions [1], large mode area [2], and highly nonlinear performance with optimized dispersion properties [3, 4]. PCFs with such attractive and appealing features are expected to become the ultimate transmission waveguide for electromagnetic waves. These fibers are also expected to provide a new optoelectronic tool in the field of imaging, telecommunications, spectroscopy, and metrology. In many of these applications, PCF is required to be cabled and placed in the form of a coil, which leads to the macro-bending-loss in the fiber. Accordingly, bend loss in photonic-crystal fibers need to be estimated. A brief description of the bending loss properties of PCFs have been reported in the literature [5], where the loss coefficient formula [6] for an arbitrary refractive index profile is used to predict macro-bending-losses in PCFs.

In this paper, we report the theoretical calculation and analysis of the bending loss properties of photonic-crystal fibers by adopting the effective index method. Earlier, the effective index method was used to obtain waveguiding parameters, such as the effective normalized frequency, cutoff wavelength, far field radiation pattern, and splice losses [1, 7–10] for PCF. Very recently, an online method for characterization of PCF from its far field radiation pattern using the effective index model has also been reported [11]. In this method, a PCF is approximated by an equivalent step index fiber. Therefore, we prefer to apply the bending loss formula [12] of step index fiber to photonic-crystal fiber instead of the loss coefficient formula for an arbitrary refractive index profile as used in [5] for estimating the bend loss properties in PCF. This provides an accurate estimation of bend loss in photonic-crystal fibers, and the results thus obtained have a similar nature to those of the macro-bending-losses of PCF mentioned in [5]. Here it is added that this method is accurate for a smaller size of air holes in the cladding since the weakly guiding approximation for photonic-crystal fiber is not violated as the difference between the effective refractive index of the core and cladding is very small (i.e., $\Delta_{\mathrm{eff}} \leq 1\%$, in [12]). Bend loss for different structures of photonic-crystal fibers at various values of the bend radius is observed. It is shown that bend loss in PCF can be controlled by varying the fiber parameters. Further, the spectral window for minimum bend loss in PCF is obtained for different values of relative air hole size and bend radius. The effect of tailoring the size of air holes *d* and pitch Λ on the spectral window is also studied, and it is observed that the range of operating wavelengths for minimum bend loss increases as the air hole size becomes larger. The bend losses are considerably large for smaller air hole size. Therefore, we expect that this study will be helpful in the design of photonic-crystal fiber with minimum bend loss for a broad spectral range.

2. THEORY AND CALCULATION OF BEND LOSS

The macro-bending-losses of optical fibers are very important not only from a practical point of view but also because they define the spectral windows in which the fiber operates and provide important information about the propagating modes of the fiber. Short wavelength edge has been observed for PCFs [1] with critical values of the bend radius. Here, we considered a 2D triangular lattice photonic crystal as a cladding of the PCF for analyzing its macro-bending-loss properties, as shown in Fig. 1. Λ is the separation between two air holes, i.e., the pitch of the lattice, and d is the size of an air hole.

To obtain bending losses in PCFs, an analogy between PCF and step index fiber has been applied.

Thus, making use of the effective index method as described in [9–11], the effective normalized frequency $V_{\rm eff}$ is given by

$$V_{\rm eff} = \frac{2\pi\rho_{\rm eq}}{\lambda}\sqrt{n_{\rm co}^2 - n_{\rm cl,\,eff}^2}, \qquad (1)$$

where $\rho_{\rm eq}$ is the core radius of an equivalent step index PCF considered to be $\rho_{\rm eq} = 0.64\Lambda$ [13] $n_{\rm co}$ is the core refractive index (i.e., $n_{\rm co}$ = refractive index of pure silica = 1.45) and $n_{\rm cl,\,eff}$ is the effective refractive index of the PCF cladding calculated by the effective index method as discussed in reference [9–11]. The average effective cladding index $n_{\rm cl,\,eff}$ exhibits strong wavelength dependence. At short wavelength the field is mainly confined to the silica, whereas at long wavelength the effective index of the field decreases. The refractive index difference between the core and the cladding increases with an increase in wavelength and decreases with a decrease in wavelength.

To deduce bending losses in PCFs, the formula for the loss coefficient of standard step index fibers due to macro-bending losses [12]:

$$\alpha(dB/m) = 4.343\left(\frac{\pi}{4\rho R_c}\right)^{1/2} \times \left(\frac{U}{VK_1(W)}\right)^2\left(\frac{1}{W}\right)^{3/2}\exp\left\{-\frac{4R_cW^3\Delta}{3\rho V^2}\right\},$$

which is used for photonic-crystal fiber with effective parameters as

$$\alpha(dB/m) = 4.343\left(\frac{\pi}{4\rho_{\rm eq}R_c}\right)^{1/2}\left(\frac{U_{\rm eff}}{V_{\rm eff}K_1(W_{\rm eff})}\right)^2 \times \left(\frac{1}{W_{\rm eff}}\right)^{3/2}\exp\left\{-\frac{4R_cW_{\rm eff}^3\Delta_{\rm eff}}{3\rho_{\rm eq}V_{\rm eff}^2}\right\}, \qquad (2)$$

where $\rho_{\rm eq}$ defines the core radius of an equivalent step index PCF; R_c is the radius of curvature of a bend in cm; $U_{\rm eff}$ and $W_{\rm eff}$ are waveguide parameters calculated by the effective index method for PCF as mentioned in [9–11]; $V_{\rm eff}$ defines the effective normalized frequency of PCF and is given by Eq. (1); $\Delta_{\rm eff}$ gives the relative refractive index difference, $\Delta_{\rm eff} = \dfrac{n_{\rm co} - n_{\rm cl,\,eff}}{n_{\rm co}}$; and $K_1(W_{\rm eff})$ is a modified Bessel function of second kind.

The wavelength dependence of $\Delta_{\rm eff}$ and $V_{\rm eff}$ predicts a loss mechanism for shorter wavelengths. Variation of bend loss values (in dB/m) at different values of bend radius for two different fractions of air filling or different relative air hole size of photonic-crystal fibers (i.e., $d/\Lambda = 0.30$ and $d/\Lambda = 0.40$) are shown in Figs. 2a and 2b.

It is seen from Figs. 2a and 2b that a short wavelength loss edge appears for PCFs, in contrast to standard fiber, where only a long wavelength loss edge is

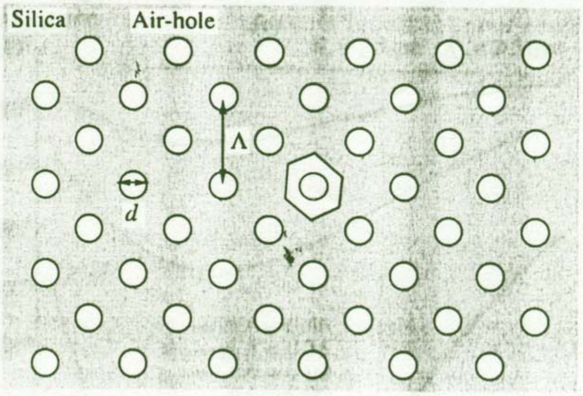

Fig. 1. Two-dimensional triangular lattice photonic crystal with air hole size d and pitch Λ.

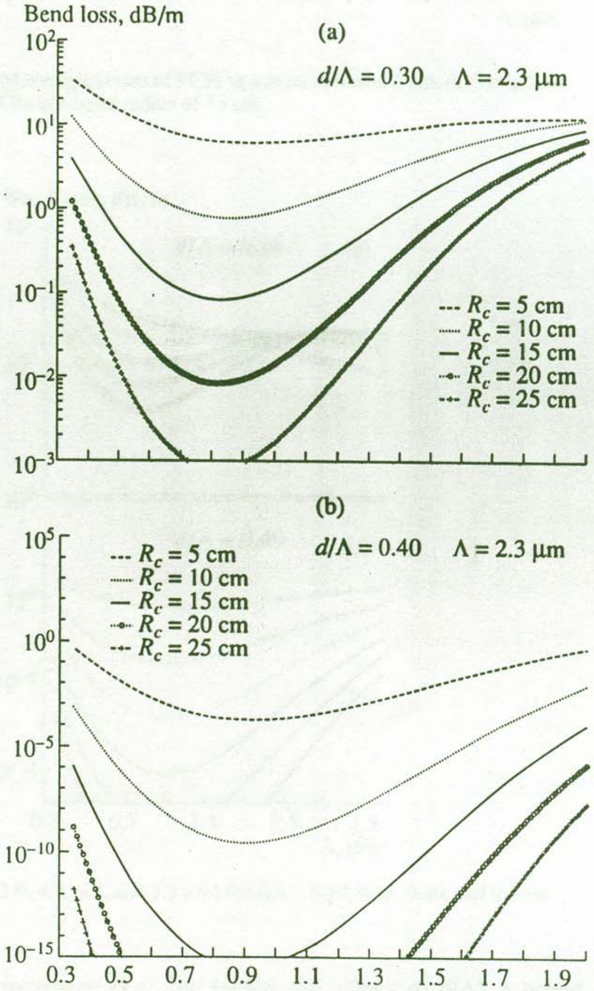

Fig. 2. (a) Variation of bend loss (dB/m) with wavelength (in μm) for different values of bend radius (in cm) at a relative air hole size $d/\Lambda = 0.30$. (b) Variation of bend loss (dB/m) with wavelength (in μm) for different values of bend radius (in cm) at a relative air hole size $d/\Lambda = 0.40$.

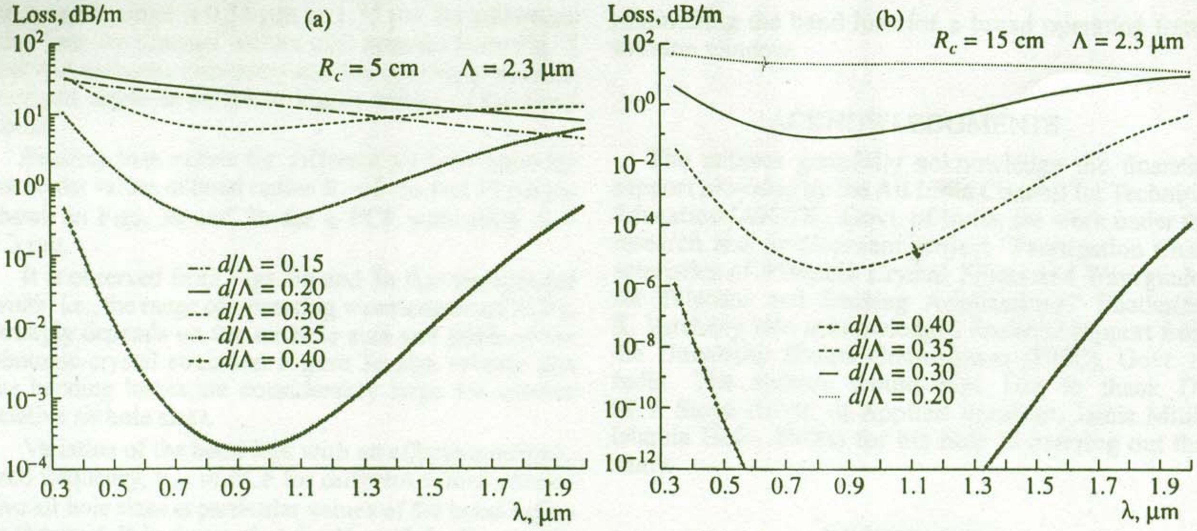

Fig. 3. (a) Variation of bend loss values with wavelength for different configurations of PCFs at a bend radius of 5 cm. (b) Variation of bend loss values with wavelength for relative air hole sizes of PCFs at a bend radius of 15 cm.

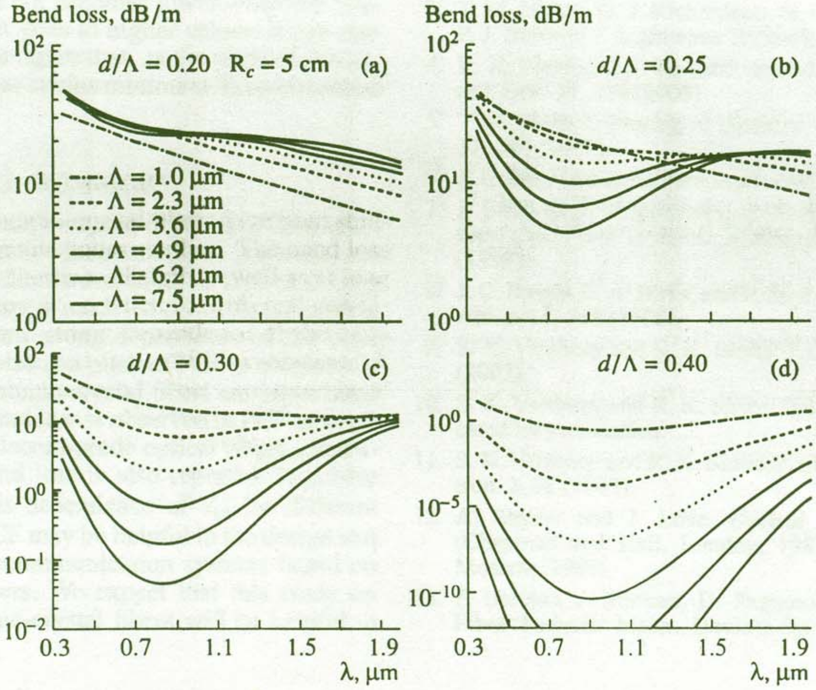

Fig. 4. Variation of bend loss for different pitch Λ values (1.0, 2.3, 3.6, 4.9, 6.2, and 7.5 μm) for d/Λ = 0.20, 0.25, 0.30, and 0.40 at a bend radius of 5 cm.

found. These two loss edges determine the range of wavelengths in which PCF can operate for low bend loss. It is further revealed from Figs. 2a and 2b that the operating wavelength ranges for low bend loss increase as the bend radius increases. It is clear that, for a particular value of the bend radius, as the size of the air holes increases (i.e., the higher the values of d/Λ), a broad range of operating wavelengths is observed.

For example, from Figs. 2a and 2b, it is clear that, at R_c = 25 cm and d/Λ = 0.30, the spectral range is 0.7 μm to 0.9 μm, while for d/Λ = 0.40 at the same bend radius, the spectral range is 0.35 μm to 1.75 μm for minimum bend loss. An unusual feature also appears from Fig. 2 that loss becomes minimum and the operating window becomes larger as we go to higher values of the bend radius.

Bending loss values for different air hole sizes for particular values of bend radius $R_c = 5$ cm and 15 cm are shown in Figs. 3a and 3b for a PCF with pitch $\Lambda = 2.3$ μm.

It is observed from Figs. 3a and 3b that the spectral width, i.e., the range of operating wavelengths of PCFs, strongly depends on the air hole size and pitch of the photonic-crystal structure. Figure 3a also reveals that the bending losses are considerably large for smaller relative air hole sizes.

Variation of the bend loss with an effective normalized frequency, V_{eff}, of PCF for different values of relative air hole sizes at particular values of the bend radius is obtained. It is shown that for $V_{\mathrm{eff}} = 2.4$, $d/\Lambda = 0.28$, and $R_c = 15$ cm, bend loss is minimum. The influence of the pitch (Λ) parameter on bend loss in photonic-crystal fibers is shown in Fig. 4. It is obvious from Fig. 4 that the bend loss is large for smaller values of relative air hole size but becomes lower when the relative air hole size d/Λ goes to higher values. It can also be revealed from the figure that, as the pitch of the lattice increases, the loss attains minima with an enhanced spectral window.

3. SUMMARY

Bend loss of photonic-crystal fibers have been studied by applying effective index method. The bend loss edge is observed at short wavelength as well as at long wavelength. Bend loss is modeled for different configurations of PCFs, and strong dependence of the bend loss on the air hole size and pitch of PCF is obtained. It is observed that photonic-crystal fibers are more bend resistant; i.e., low bend loss is observed in PCF as compared to standard telecom-grade optical fibers. Dependence of V_{eff} on bend loss is also reported. It is here emphasized that this dependence of V_{eff} for different configurations of PCF may be helpful in the design and development of telecommunication systems based on photonic-crystal fibers. We expect that this study on bend loss in photonic-crystal fibers will be helpful in minimizing the bend loss for a broad operating transmission window.

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