Analyses of bending losses in photonic crystal fiber using FDTD algorithm and conformal transformation of index profile

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1. Introduction

Recently, photonic crystal fibers (PCF) have attracted much scientific and commercial interest. The research and design work for PCF starts from accurate modal analysis of the fiber. In this, predicting the bending losses of PCF is an important problem. It is well known that a radiation loss occurs when a fiber is bent. The bending loss has been regarded as an adverse effect in the context of optical transmission. However, bent fibers can also be optimized as novel optical components which can be employed in optical communications or optical sensing.

This research presents both simulation and experimental investigation on bending loss of PCF. In the fist part, the basics of 3D-FDTD modeling for bending loss of PCF are explained. The second part discusses the results of 3D-FDTD simulations on bending loss at difference bending radius for a typical PCF and the comparison between simulation and experiment results

2. Simulation and comparison with experiment

Because of Micro-structure in cladding, predicting the bending losses of PCFs is a challenging problem. Most of the methods developed for conventional fibers like antenna-theory for standard fiber, circularly symmetric index profile and cannot be applied to PCFs. Here, we apply FDTD algorithm which is particularly well suited to simulate light field dynamics and propagation in finite photonic crystal defect structures like PCFs to calculate bending loss. Beside that, the conformal transformation is used to replace the bent fiber with a straight fiber that has an equivalent refractive index profile(1). The equivalent refractive index profile is found by expressing the scalar wave equation in terms of a local coordinate system that follows the curvature of the fiber. A fiber, bent in the x-direction for example, can be represented by a straight fiber with an effective refractive index distribution of:

$$n_{eq}^2(x,y) = n^2(x,y)(1+\frac{2x}{R_b})$$

Where, R_b is the radius of curvature and n(x, y) is the refractive index profile of the straight fiber. Thus, by applying the transform in above equation to the refractive index profile of a straight PCF, we can define an index profile that mimics the modal properties of a bent holey fiber(2).

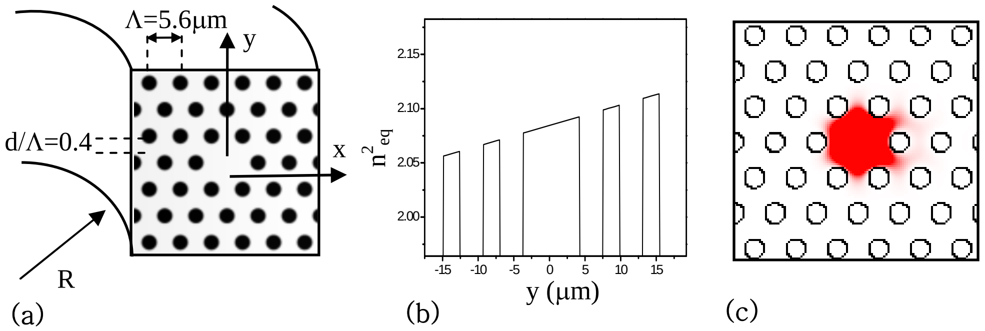
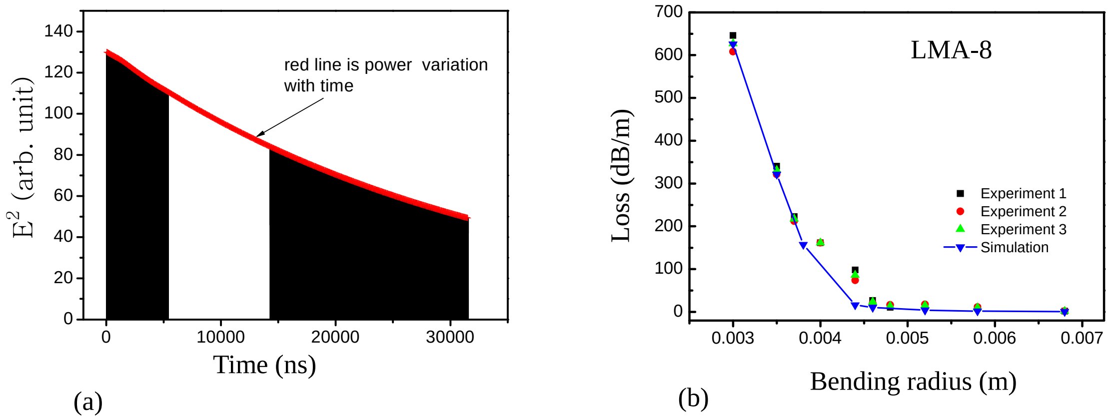


Fig.1: (a) Cross-section of bent PCF, (b) The equivalent refractive index distribution of bent PCF, (c) mode profile in bent fiber

For example, the refractive index profile of PCF LMA-8 with bend, shown in Figs. 1(a), is transformed using this equivalent refractive index equation for a bend radius of 4.5 mm, as shown in Fig. 1(b). These figures show clearly that the transform superimposes a gradient onto the refractive index of the straight fiber in the direction of the bend. One can also see, intuitively, that the mode will distort outwards in the direction of the bend. Furthermore, since the gradient is proportional to the bending radius, it is obvious that the mode will become increasingly distorted at tighter bend radius. Fig. 1(c) show the distribution of electric field on a cross section of bent PCF(3).

By using this simulation method, we also calculated bending loss as function of bend radius at given wavelength λ=1550 nm for PCF LMA-8 (Λ=5.6μm, d/Λ=0.49). For each given bend radius, the simulation provides the square of electric field variation as a function of time $E^2(t)$. But, power P ~ amplitude of E^2, so we can have the power variation as function of time from envelope of $E^2(t)$ (Fig. 2(a)). By fitting the envelope with exponential function, $P(t)=P_0\exp(-\alpha' t)$, we can obtain the loss factor per unit time. The light propagate along the fiber with group velocity $v_g=c/n_{eff}$ (c is speed of light in free space, n_{eff} is effective index) so we can convert loss factor per unit time α' to loss factor per unit curvature length $\alpha=\alpha'/v_g$. For a conversion to a dB-scale α should be multiplied by $10\mathrm{x}\log_{10}(e)$(4).



(a) (b)

Fig. 2: (a) E^2 (or P) as a function of time, (b) comparison between simulation and experiment for LMA-8

The bending loss depends on bending radius for LMA-8 is shown in solid line of Fig. 2(b). These results show that, equivalent refractive index profile method and 3D-FDTD algorithm provide a useful method for predicting the bending loss which any given holey fiber is practical to use.

For LMA-8 bending loss has been measured with difference bending radius at wavelength λ=1550nm. In experimental setup, the input source was a tunable laser, and optical power meter was used to measure output power. We measured the bend loss in the bend radius range of 3 mm to 7 mm inclusive, in increments of 0.3 mm and at the wavelength 1550 nm. The experiment result is shown in Fig. 2(b) in comparison with simulation. The agreement between simulation and experimental results confirming the validity of our simulation method

3. Conclusion

Simulation method of bending losses for a holey fiber has been presented. Bend loss characteristics of the some typical holey have been investigated theoretically and experimentally. There is agreement in comparison between simulation and experiment. Also, the result shows that, holey fiber has lower loss then conventional fiber. This research can be applied to design new structure of photonic crystal fibers with low bending loss or fiber–bend–based sensors.

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