Numerical simulation and analysis of losses in air-core plastic photonic bandgap fibers

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The loss properties of air-core plastic photonic bandgap fibers are analyzed by multipole method. Despite the relatively large absorption loss of plastics (PMMA), the contribution of material absorption loss can be reduced significantly through appropriate selection of operating wavelength, number of cladding air-hole rings, radius of air-core, and position of photonic band gap. The transmission loss in this type of fiber can be decreased by an order of magnitude in comparison with that of conventional plastic optical fiber.

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PMMA (polymethyl methacrylate) plastic optical fiber (POF) is a low-cost, easy-to-use, flexible data transmission medium. It is especially well suited to short distance, high connector-density systems such as LANs[1]. Compared with silica optical fiber, PMMA POF has larger material absorption loss. The loss limit of PMMA POF at 650-nm wavelengh is about 100 dB/km. The total transmission loss of practical PMMA optical fiber is mostly between 150 and 180 dB/km[2].

An effective approach that reduces the loss of optical fiber with PMMA core is substituting the hydrogen in C − H bond with deuterium, i.e., all-deuterated PMMA (PMMA - d8) core fiber. The losses of PMMA-d8-core fibers can be reduced to 20 dB/km at the wavelength of 680 nm, but interest in deuterated polymers is limited due to the prohibitive material costs. Photonic crystal fibers (PCF) provide a new approach to solve the problem. Photonic bandgap fibers guide light by the photonic bandgap effect and confine light to the air-core of the fiber. If the band gap occurs at $\beta/k_0 < 1$, where β is propagation constant, and k_0 is the free space wave number, it is possible to transmit light in the air-core of the optical fiber. So most of the light energy can propagate in the central air core, and then it is possible to reduce the material absorption loss significantly.

The cross section of an optical fiber analyzed by this paper is shown in Fig. 1. The air-core of the fiber is formed by replacing the inner seven air cylinders (type 1) or 19 air cylinders (type 2) in a triangular lattice with a larger air cylinder. The cross section of type 1 and type 2 is the same except the core radius. N is defined as the number of cladding rings ($N = 4$ in the Fig. 1). Because the air-core defect in type 2 is bigger, lower transmission loss can be obtained and so type 2 is preferential here. Its basic parameters are: the radius of the central air-core defect $r_c = 2.1\Lambda$ and the radius of the air hole in cladding $r_0 = 0.47\Lambda$, where Λ is the center-to-center distance between the two nearest air holes in the cladding, and normalized frequency $k_0\Lambda = 9.95$. The index of PMMA takes the value 1.49. The band gap formed by this structure is shown in Fig. 2, where $k = 2\pi/\lambda$.

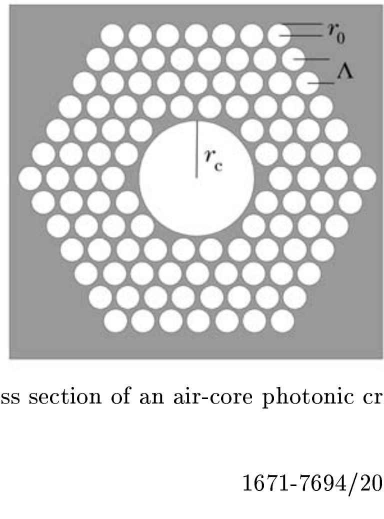

Fig. 1. Cross section of an air-core photonic crystal fibers.

Multipole method used by this paper is a new numerical approach developed by White and Kuhlmey[3,4]. According to group theory[5], the symmetry operation of the PCF forms a C_{6v} point group, as a result, the guided modes can be divided into eight classes. And they have four non-degenerate and four degenerate modes. The relationship between the mode classes and the distribution of z component of Poynting vector is analyzed in Ref. [6]. The results indicate that the degenerate class modes 3 and 4 resemble the fundamental HE_{11}mode of conventional step-index fiber, and the losses of the two class modes are relatively lower than the others. So only these two class modes are discussed in this paper.

Firstly, we ignore the material loss and calculate the influence of number of rings N on the leakage loss. Air-core photonic crystal fiber with N and its leakage loss

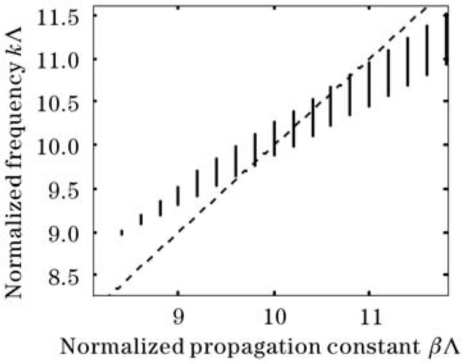

Fig. 2. The band gap diagram of triangular structure with $r_0/\Lambda = 0.47$, solid lines show band gaps at a fixed $\beta\Lambda$, dotted line is air line (n=1).

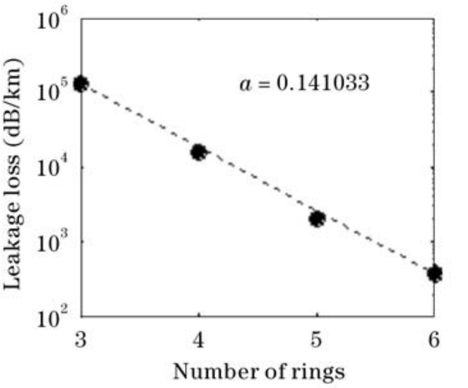

Fig. 3. Variation of leakage loss of an air-core PCF with the number of air hole rings in the cladding.

have following relation[7]

$$L_{\text{leak}} = Ca^N, \tag{1}$$

where a is a constant depending on concrete structure and mode, and C is also a constant. According to Fig. 1, after calculating and fitting data, we have $a = 0.141033$, $C = 4.6093 \times 10^7$. Figure 3 illustrates this relation. The solid circles indicate the actual computation results, and the dashed line is the approximation curve calculated by Eq. (1). We find that the exponential approximation is satisfactory. In the vicinity of wavelengths of 650 and 780 nm for transmission window of PMMA fiber, where we set material loss to be 100 and 800 dB/km[1], respectively, the leakage losses of class 3 and 4 can drop below 1 dB/km for $N \geq 9$. Of course, this value is calculated for an ideal PCF, i.e., without any air-hole deformation or fiber nonuniformity, so it can be regarded as a lower limit for the propagation loss in a particular PCF.

In air-core PCF, some parts of light propagate directly in the air-core, and some will be absorbed and leaked through transverse cladding. Total loss (L_{total}) depends on the structure of cladding (especially the number of air-hole rings of cladding) and the cladding material. We use the term L_{leak} to denote the leakage loss related only to the structure of fiber cladding, and $L_{\text{abs}}\alpha$ to represent the absorption loss related to material, where L_{abs} denotes the absorption loss of the host bulk material (PMMA), α is the percentage of optical field propagating in the host material. Then we have

$$L_{\text{total}} = L_{\text{leak}} + L_{\text{abs}}\alpha. \tag{2}$$

Once the structure of fiber (N) is fixed, L_{leak} in Eq. (2) is also determined. So α can be achieved via calculating the variation of L_{total} with different L_{abs}. Figures 4 and 5 depict the curves of the total loss as a function of material loss with $N = 4$ and $N = 5$. We can know from two figures that once the leakage loss is decided, the total loss has linear dependence with material loss and the linear coefficient α. Of course α is commonly different for different fiber structures and different guided modes. For the type 2 structure, we got the same result: $\alpha \approx 0.0297$ for $N = 4$ and $N = 5$. In fact, we find the number of rings N has little influence on the value of α for $N \geq 2$, that is to say, the increasing N has little influence on the percentage of optical field in the PMMA medium.

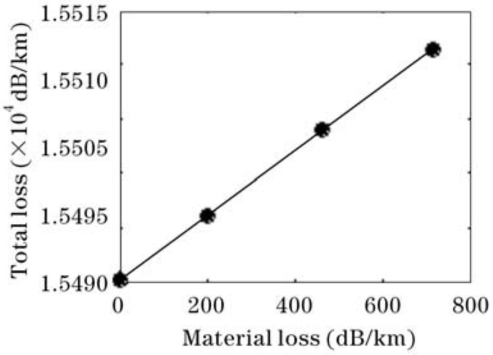

Fig. 4. Variation of total loss in an air-core PCF (N=4) with the material loss in PMMA.

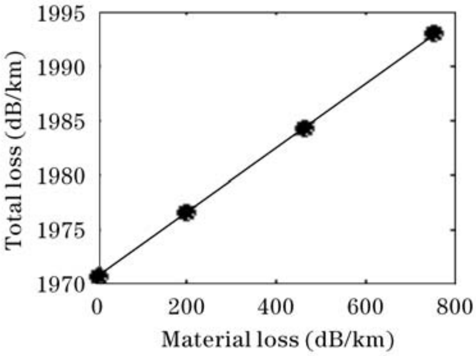

Fig. 5. Variation of total loss in an air-core PCF (N=5) with the material loss in PMMA.

Assuming that the material loss of PMMA is 100 dB/km at the wavelength of 650 nm, the absorption loss of the PCF should be $100\alpha = 2.97$ dB/km. The leakage loss can drop below 1 dB/km for $N \geq 9$, hence the total loss should be below 10 dB/km. If the wavelength is 780 nm, and the material loss is set as 800 dB/km, then its absorption loss is 23.8 dB/km. In this way, the request of middle-short distance data transmission can be satisfied at these two wavelengths. Leakage loss is far smaller than the loss brought by the material loss of PMMA for $N \geq 9$, so $N = 9$ is large enough for this structure. The increase of N only adds additional complexity of the fiber structure and has no contribution on decreasing the transmission loss of this kind of fiber.

In the above calculation, we focus on the result of only one frequency point for type 2. In the following, we will analyze how α for types 1 and 2 varies with frequency (corresponding to different positions in band gap), the core radius of type 1 analyzed here is taken as 1.262Λ, the result can be seen in Fig. 6. It follows that $\alpha_{\text{type 1}}$ is much larger than $\alpha_{\text{type 2}}$. As the core radius of the fiber increases, the part of light propagating in cladding becomes smaller, so α becomes smaller. The value of α of type 2 will also vary with frequency position in band gap (see Fig. 7). Figure 8 shows the variation of L_{leak} and α for type 2 with normalized frequency. From Figs. 6, 7, and 8, it can be concluded that when the frequency point is in the vicinity of the center of the band gap, α is relatively smaller, and the variation of α curve is smoother, L_{leak} is also smaller.

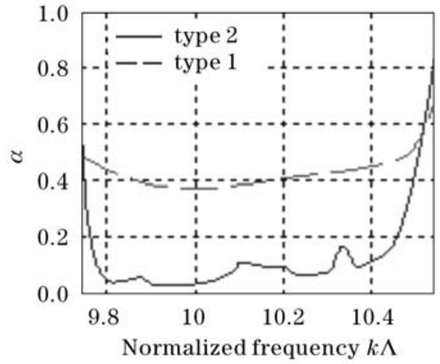

Fig. 6. The variation of α with normalized frequency $k\Lambda$ for air-core PCFs of type 1 and type 2.

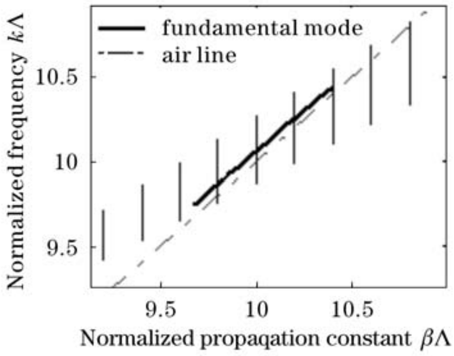

Fig. 7. Illustration of fundamental-mode normalized frequency $k\Lambda$ in band gap of triangular structure with $r_0/\Lambda = 0.47$.

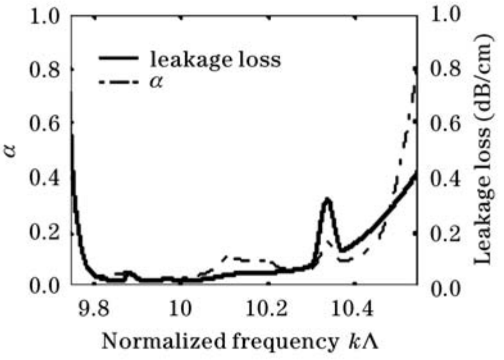

Fig. 8. Variation of leakage loss and α with normalized frequency $k\Lambda$ for air-core PCF of type 2.

As the frequency points of mode approaching the edge of band gap, α increases, and so does L_{leak}. The variational rules of both α and L_{leak} are similar. The reason is that when normalized frequency is in the vicinity of the center in band gap, the capability of a cladding to confine light is much stronger, so the majority of light is confined in the air core. But as the normalized frequency point is approaching the edge of band gap, the confinement becomes weaker. As a result, the percentage of light propagating in cladding increases, and α and L_{leak} also increases.

In conclusion, the loss properties of air-core PMMA photonic bandgap fiber are analyzed by using multipole method. The numerical results show that the leakage loss of the fiber becomes smaller as the number of air-hole rings in cladding increases; its transmission loss mainly depends on the material absorption loss once the leakage loss is small enough; and the material absorption loss has different effects on the transmission loss as the frequency is in different positions in band gap. So reasonable design can not only increase the transmission distance but also make it possible to transmit beam in wider waveband where material loss is larger, which will significantly extend the useful frequency range of PMMA optical fiber.

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