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Numerical analyses of splice losses of photonic crystal fibers

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ABSTRACT

Splice losses between a photonic crystal fiber (PCF) and a single mode fiber (SMF) or a PCF are numerically investigated by using finite element method (FEM) with the circular perfectly matched layer (PML). Results show that the splice loss between a SMF and a PCF with air holes completely collapsed can reach many times of that between a SMF and a PCF without air-hole collapse. We calculate the rotation losses between two identical PCFs of three kinds: large mode area, polarization maintaining and grapefruit. It is shown that for the large mode area PCF and the grapefruit PCF, the rotation losses are sensitive to the wavelength when the rotation angle is larger than zero degree. The non-circular mode field distribution is the main source of the rotation loss.

1. Introduction

In recent years PCFs, also called microstructure fibers or holey fibers, have attracted much attention due to their unique waveguide properties, such as endless single-mode guiding [1], tailorable group-velocity dispersion [2], high nonlinearity [3] and flexible designing, etc. PCFs are typically classified into two types: index-guiding PCFs [4], which guide light by total internal reflection mechanism as the conventional fibers, and photonic bandgap fibers [5], which confine light in the low-index core by using photonic bandgap effects. PCFs have been used for fiber-optic devices and fiber sensing applications that are difficult to be realized by conventional fibers.

In many experiments and applications, PCFs are often needed to be spliced with conventional fibers, the splice loss of which mainly comes from fundamental mode mismatch, angular misalignment and core offset [6]. Air-hole collapse of PCFs is another source of splice loss, but it also can be used to reduce splice loss when the two fibers have mode mismatch [7]. Many methods have been proposed for low-loss splicing of conventional fibers with PCFs by using a fusion splicer [8,9] or a CO_2 laser [10,11], and the theory used for two conventional fibers is applied to analyze the splice loss between PCFs and conventional fibers [10,12]. The splicing of two PCFs is also confronted in the applications of PCFs, the experiment of which has been done by Bruno Bourliaguet et al. [13] and the results showed that the splice loss is more sensitive than that of a conventional fiber with a PCF.

In this paper, splice losses resulting from the fundamental mode mismatch between a PCF and a SMF or a PCF are investigated by using FEM with the circular PML [14,15]. By ignoring other factors, we first calculate the splice loss between a PCF and a SMF with air-holes collapsed. The results show that when the PCF's air holes are completely collapsed the splice loss can be many times of that when the PCF without air-hole collapse. Second, we focus our study on the rotation losses of two identical PCFs of three types of configurations, i.e., large mode area, polarization maintaining and grapefruit, without air-hole collapse. From the calculation results, we find that the rotation losses are sensitive to wavelength for the large mode area PCF and grapefruit PCF when the rotation angle is larger than zero, and increase with increasing of the rotation angles.

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2. Theoretical formulation

FEM has been one of the most successful numerical methods in solving waveguide problems owing to its high flexibility and precision. By properly choosing finite triangular elements across the profile of PCFs and using the continuous conditions on the boundary of each element, FEM has been widely used to solve electromagnetic problems in PCFs. For a better description of the mode field of PCFs, the complex areas are often chosen to have finer elements than the other parts. In addition, an anisotropic material is assumed in the calculation as a computational window border (i.e., PML) which will absorb the entire incident field without any reflection. PML surrounding the profile of the PCF are often chosen to have eight square regions. Recently, Pierre Viale proposed a kind of circular PML [15] which was shown to be more simple and efficient in the study of electromagnetic problems in PCFs.

By using FEM we can calculate the fundamental transverse mode distributions of PCFs and SMFs. Then the effective areas of the fundamental modes of the fibers can be given by [16]

$$A_{eff} = \frac{\left(\int\int_{-\infty}^{+\infty} |E(x,y)|^2 dxdy\right)^2}{\int\int_{-\infty}^{+\infty} |E(x,y)|^4 dxdy} \tag{1}$$

where $E(x, y)$ is the transverse electric field distribution of the fundamental mode of the fiber. From Eq. (1), the effective radius $\omega_{eff} = (A_{eff}/\pi)^{1/2}$ can be obtained. Under the Gaussian profile approximation of the fundamental modes, the splice loss α_{ps} between a PCF and a SMF can be approximately expressed by [9]

$$\alpha_{ps} = -20 \log\left(\frac{2\omega_{PCF}\omega_{SMF}}{\omega_{PCF}^2 + \omega_{SMF}^2}\right) \tag{2}$$

where ω_{PCF} and ω_{SMF} are the fundamental mode radii of the PCF and the SMF, respectively.

During the splicing process, air-hole collapse is often inevitable for PCFs. For the PCFs with a few air holes, such as grapefruit PCF, the effect of air-hole collapse has been experimentally studied [17]. For the PCFs with a large number of air holes in the cladding, the relation between the air-hole radius d and pitch Λ (the distance between nearest neighbor air holes) is approximately given by [18,19]

$$\left(\frac{\Lambda}{\Lambda_0}\right)^2 = \frac{\frac{\sqrt{3}}{2} - \frac{\pi}{4}\left(\frac{d_0}{\Lambda_0}\right)^2}{\frac{\sqrt{3}}{2} - \frac{\pi}{4}\left(\frac{d_0}{\Lambda}\right)^2} \tag{3}$$

where d_0 and Λ_0 are the initial air-hole radius and the pitch, respectively.

Generally, the splice loss between PCFs and conventional fibers can be calculated by using Eqs. (1) and (2). However, the contribution of the microstructure to the mode fields makes the splice loss calculated by Eq. (2) inaccurate for splicing two PCFs. The rigorous analysis of the splice α_p between two PCFs is given by the mode overlap integral [20]:

$$\alpha_p = -10 \log\left|\left(\frac{\int\int E_p \cdot E_s dxdy}{\sqrt{\int\int |E_p|^2 dxdy}\sqrt{\int\int |E_s|^2 dxdy}}\right)\right|^2 \tag{4}$$

where E_p and E_s are the transverse electric field distributions of the fundamental modes of PCFs. This equation reveals that the splice loss α_p is closely related with the angle which comes from the inner product of E_p and E_s, so we define this type of splice loss as rotation loss to distinguish it from the conventional splice loss.

3. Numerical results

3.1. Splicing a PCF to a SMF

As examples, two representative fibers, a large mode area PCF *LMA*-10 and a single mode fiber *SMF*-28, are considered to analyze the splice loss between a PCF and a SMF by using Eqs. (1) and (2). For *LMA*-10, due to its large number of air holes in the cladding, we use Eq. (3) to calculate the new air-hole radius and the new pitch when the air holes are collapsed. The schematic illustration for *LMA*-10 is shown in Fig. 1. *LMA*-10 comprises of seven layers of air holes with one central air hole missed. Its cladding diameter is 125 μm and its pitch is $\Lambda = 7.14$ μm with normalized air-hole diameter being $d/\Lambda = 0.46$. The refractive index n of the pure silica background is given by the Sellmeier equation [21] as follows:

$$n^2 = 1 + \frac{0.6961663\lambda^2}{\lambda^2 - 0.004679148 26^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.0135120631^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 97.9340025^2} \tag{5}$$

where λ is the wavelength.

To calculate the fundamental mode distributions of *LMA*-10 one needs only to consider one quarter of the cross section due to their symmetry [22]. Our calculation of the fundamental mode field diameter (FMFD) of *LMA*-10 is 9.1 μm for $\lambda = 1.55$ μm, which agrees with Ref. [9]. In the range of $d/\lambda = 0$–0.46, the confinement losses are less than 10^{-4} dB/m, so it can be neglected in the simulation. We consider a full adiabatic process [23], so that the fundamental mode would not couple to any other modes while propagating through the splice region. We only calculate the splice loss caused by the mode mismatch between *LMA*-10 and *SMF*-28 without considering angular misalignment, core offset and Fresnel reflection at the interface.

Fig. 2 shows the effective index (solid line) and the fundamental mode radius (dash line) versus the air-hole radius of *LMA*-10 for $\lambda = 1.55$ μm. From Fig. 2 it can be seen that the effective index and fundamental mode radius decreases with the increasing of air-hole radius. The maximum refractive index is 1.444, which is close to the background material, and the maximum mode radius is 41 μm, which is close to the silica cylinder radius, when the air holes are completely collapsed. Fig. 3 shows the splice loss between *LMA*-10 and *SMF*-28 (FMFD = 10.4 μm for $\lambda = 1.55$ μm [8]) versus the air-hole radius. It can be seen that the splice loss decreases with increasing air-hole radius, but slightly increases when the air-hole radius is larger than $d = 1.148$ μm, as shown in the insert of Fig. 3. Zero splice loss is found at $d = 1.148$ μm and the maximum value is 12.05 dB when $d = 0$, which is about 150 times of the splice loss when without air-hole collapse.

The FMFD increases with decreasing air-hole radius because smaller air holes have lower restriction on the mode field as shown in Fig. 2. However, even if air holes are completely collapsed, the

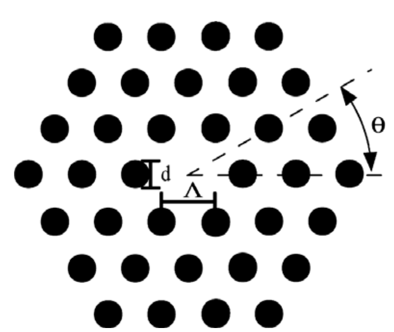

Fig. 1. Microstructure scheme of *LMA*-10.