ANALYTICAL MODELING AND IMPLEMENTATION FOR SPLICING OF PHOTONIC CRYSTAL FIBERS

Tahreer Safa’a Mansour
Institute of Laser for Postgraduate Studies, University of Baghdad, Baghdad, Iraq
Corresponding Author: TahreerSafa’a Mansour
Email: tahreer@ilps.uobaghdad.edu.iq
https://doi.org/10.26782/jmcms.2019.12.00011

Abstract

The difficulty of fusion splicing hollow-core photonic Crystal fibers (HC-PCFs) and solid-core (SC-PCFs) to conventional step index single mode fiber (SMF) has severely limited the implementation of PCFs. To make PCFs morefunctional, we have developed a method for splicing HC-PCF and SC-PCF to a SMF using a commercial arc splicer. A repeatable, robust, low-loss splice between the PCFs and SMF is demonstrated. In this paper, comprehensive theoretical, simulation and empirical -MZI based on splicing PCF between two single mode fibers. Adopting of MZI based on SMF and PCF is presented. Theoretical model of computing MFD and relative hole size is used to investigate losses with respect to splicing region. In addition, modeling of MZI using Opti Bpm yields a flexible solution to investigate the splicing effects and finding the optimum point of losses. Both MZI based on SC-PCF and HC-PCF are used in this article. In this section, optimization of splice loss of joints between PCF and SMF is carried out. For the analysis, we use two solvers OptiBPM and OptiMode, and codes written by MATLAB software.

Keywords: Fusion splicing fibers, microstructure fabrication, photonic crystal fiber.

I. Introduction

Photonic crystal fibers (PCFs), which are also called microstructure optical fibers or holey fibers, have been investigated with great interest and have considerably altered the traditional fiber optics [I-III] since they appeared in the mid1990s [IV]. PCFs have a periodic array of micro-holes that run along the entire fiber length. They typically have two kinds of cross sections: One is an air–silica cladding surrounding a solid silica core, and the other is an air–silica cladding surrounding a hollow core. The light-guiding mechanism of the former is provided by means of a modified total internal reflection (index guiding), while the light-guiding mechanism of the latter is based on the photonic bandgap effect (PBG guiding). Because of their freedom in design and novel wave-guiding properties, PCFs have been used for a number of novel fiber-optic devices and fiber-sensing applications that are difficult to be realized by the use of conventional fibers. PCFs will have a
great potential for commercial products in many applications in the next decade [V]. To realize the full potential of PCFs, it is necessary to splice them to SMFs. However, because PCFs have micro-hole structures that are totally different from conventional fibers, splicing different PCFs to conventional fibers is a significant challenge. The micro-hole collapse phenomenon and its effect on splice loss is a new issue that is very important to the understanding of splice loss. To explore novel splice methods between these different types of fibers, a systematic investigation needs to be conducted, which has not been done so far. Since Bennett et al. [VI] first reported experimentally splicing SMFs and PCFs in 1999, many splice methods have been proposed for PCFs. One solution is to design special solid-core PCFs that have the same mode field diameters (MFDs) as SMFs [VII-VIII] or to design PCFs with a doped core [X-XI] that will guide light even when the air holes have completely collapsed during splicing. However, those methods will limit the flexibility in PCF designs. For solid-core PCFs and SMF having similar MFDs, low-loss splices were achieved by using union splicers [XII-XIII] or CO2 lasers. Another type of low-loss high-strength splice between a solid-core PCF and an SMF having similar MFDs was achieved by using a gradient-index fiber lens [XIV-XV]. For hollow-core PCFs and SMFs having similar MFDs, low-loss splices were reported by using fusion splicers. For small-core PCFs and SMFs. In this paper, we investigate the nature of micro-hole collapse when splicing and its effect on splice loss. Different kinds of PCFs have different micro-hole structures, and the properties of heat-induced collapse when splicing is quite different.

II. Principle of Splicing PCF to SMF

Splicing is used to permanently join two optical fibers where no additional changes are expected to be made to those fibers at that juncture. There are two ways to splice optical fibers: mechanical and fusion. In a mechanical splice, the fibers are held together with ends touching inside some type of sleeve. While, in fusion splicing, the two fibers are literally welded, or fused together. This makes for a strong joint that exhibits very low loss and virtually no reflection. Splicing of PCF and SMF process have many sensitive parameters that need precise adjusting to achieve low loss of splicing process. Parameters of the splicing process include arc period, fusion current, hole size, an overlap and offset space that need high attention of applicability as well as a clear interface of splicing joint of different fiber structure. Despite that, the splicing joint is of high sensitivity, which frequently turns to damage and an increased of light reflection may result. The factors that play a part in the splice losses includes the transverse counterbalance, the angular misplacement, different fiber mode field with fiber structure’s shape variety. The main difficulties of splicing process can be expressed by the incongruity of fiber mode field in addition to collapsing of the air hole which affects the guiding property of the light of the PCF and hence upsurges the losses. However, in a specific situation, the failure of the air holes may lower the loss due to the increase of match probability of the fiber mode field. To avoid or minimize the air hole collapse in splicing PCF and SMF, an effective way is to choose a weaker fusion current and a shorter fusion time compared to the parameters of splicing SMF/SMF when fusion splicing PCF/SMF. However, a suitable arc energy should be obtained to soften the tips of the PCF and the SMF to achieve a good mechanical strength of the joint and at the same time minimize the
collapse of air holes. Therefore, there is a tradeoff between the splice loss and the mechanical strength. Another important parameter is “overlap” means the overlap distance in which the two fibers are pushed further together because they have been softened as compared to when they merely touched each other in butt coupling. The tip part of the PCF is not softened enough when the arc discharge energy is low; therefore, a large overlap may cause bend misalignment when the two fibers are pushed together, thus increasing the coupling loss. Therefore, choosing a suitable overlap during splicing is also very important Because the softening point of the PCF is lower than that of the SMF, it is better to introduce a suitable offset, For fusion splicing SMFs and PCFs having similar MFDs, a low-loss joint with good mechanical strength can be formed by choosing a suitably weak fusion current; short fusion time, offset, and overlap to minimize the collapse of air holes; and well melt two fibers together. However, for splicing small-core PCFs and SMFs, the mode field mismatch can cause a large splice loss even when the air holes do not collapse.

III. Theoretical overview for splicing PCF to SMF

The basic PCF structure to be considered is shown schematically in Fig. 1. The cladding region of the fiber consists of a triangular lattice of air-holes, with a missing air-hole defining the core. In some of the designs considered, the core is doped to increase the refractive index. The defining parameters of the structure are thus the physical pitch (distance between nearest-neighbor air-holes) which we denote $\lambda$, the air-hole diameter, $d$, and possibly the diameter and index contrast of the doped core. We assume that the pitch decreases during the hole collapse so that the total silica area remains constant. Neglecting the absence of a hole at the core (which is justified for a sufficiently large number of cladding air-holes), this yields the relation [XVI]:

$$\left(\frac{\lambda}{\lambda_0}\right)^2 = \frac{\sqrt{3} \pi (d_0)^2}{\frac{\sqrt{3} \pi}{2}(\lambda_0^2)}$$  \hfill (1)

Where $\lambda_0$, $d_0$ are the initial values of pitch and hole size, respectively. From this formula it is seen, that the collapse of large air-holes can lead to quite significant changes in $\lambda$.

The field distributed within such a fiber can be accurately calculated by using a full-vector FEM [V]. This PCF is endlessly single mode for $d/\lambda \leq 0.45$. The mode-field distribution is approximately Gaussian and the MFD can then be obtained from the field distribution. There are different definitions of MFD, for example, near-field root-mean square (rms) MFD and Gaussian MFD. These definitions would give the same results if the field distributions were strictly Gaussian. However, for the complex geometry of the PCF considered here, we found that the difference between the MFD definitions can give significantly different results. The Gaussian MFD definition is used here because, for the PCF studied in this paper, it gives better results in terms of loss estimation. To evaluate the MFD of PCF, the transverse electrical-field components were firstly calculated by using the FEM. The MFD was then obtained by numerical integration of the electrical-field components according to the definition of MFD. The MFD
(W_{PCF}) increases approximately linearly with pitch Λ and decreases with an increase in \(d/Λ\). The latter is expected because the light confinement is better for relative larger air-hole diameters.

The relation of MFD (W_{PCF}) as function of Λ for \(d/Λ\) is given by [XVIII]:

\[
ω_{PCF} = \left[-0.549 \left(\frac{d}{Λ}\right) + 0.8562\right] Λ + \left[0.01298 \left(\frac{d}{Λ}\right)^{-3} + 0.07\right]
\]

(2)

It should be mentioned that Eq. (1) can also be used for other operating wavelengths by applying the scaling property of the Maxwell’s equation. In fact, Eq. (2) may be generalized to calculate the normalized mode-field radius (W_{PCF}/Λ) as function of \(d/Λ\) and \(λ/Λ\), given by [XIX]

\[
\frac{ω_{PCF}}{Λ} = \left[-0.549 \left(\frac{d}{Λ}\right)\right]
\]

According to Eq. (1) and Eq. (2), we get[XXIII]

\[
\frac{d}{Λ} = \frac{d_0(1-r)}{Λ_0 \sqrt{1 - \sqrt{3π}/6 \left(\frac{d_0}{Λ_0}\right)^2 + 1 - \sqrt{3π}/6 \left[\frac{d_0(1-r)}{Λ_0}\right]^2}}
\]

(4)

where \(r\) is the collapse ratio of the air holes given by \(r = (d_0 - d)/d_0\) with \(0 ≤ r ≤ 1\).

According to Gaussian beam propagation formalism, the maximum power coupling between PCF and an SMF, for perfectly aligned joint is given in terms of the above modal spot sizes [XX]

\[
η = \left(\frac{2W_{PCF}W_{SMF}}{W_{SMF}^2 + W_{PCF}^2}\right)^2
\]

(5)

where \(W_{SMF}\) and \(W_{PCF}\) are the spot sizes of the SMF and PCF, respectively.

Therefore, the splice loss between PCF and an SMF in absence of any misalignments is obtained as

\[
α = -20log \left(\frac{2W_{PCF}W_{SMF}}{W_{SMF}^2 + W_{PCF}^2}\right)
\]

(6)

Again, the power coupling between PCF and an SMF in presence of transverse misalignment between core centers of PCF and SMF is given by

\[
η_T = \left(\frac{2W_{PCF}W_{SMF}}{W_{SMF}^2 + W_{PCF}^2}\right)^2 \cdot \exp \left(\frac{-2u^2}{W_{SMF}^2 + W_{PCF}^2}\right)
\]

(7)
where \( u \) is the transverse offset.

Therefore, the splice loss between PCF and an SMF in presence of transverse misalignment can be written as

\[
\alpha_T = -20 \log \left( \frac{2w_{PCF}w_{SMF}}{w_{SMF}^2 + w_{PCF}^2} \right) + 4.34 \left( \frac{-2u^2}{w_{SMF}^2 + w_{PCF}^2} \right)
\]  

(8)

Further, the power coupling between PCF and an SMF in presence of angular or tilt misalignment between core centers of PCF and SMF is given by

\[
\eta_\theta = \left( \frac{2w_{PCF}w_{SMF}}{w_{SMF}^2 + w_{PCF}^2} \right)^2 \exp \left( \frac{(k_0 \theta w_{PCF}w_{SMF})^2}{2(w_{SMF}^2 + w_{PCF}^2)} \right)
\]

(9)

where \( \theta \) is the tilt offset.

Therefore, the splice loss between the PCF and SMF in presence of angular or tilt misalignment can be written as

\[
\alpha_\theta = -20 \log \left( \frac{2w_{PCF}w_{SMF}}{w_{SMF}^2 + w_{PCF}^2} \right) + 4.34 \left( \frac{(k_0 \theta w_{PCF}w_{SMF})^2}{2(w_{SMF}^2 + w_{PCF}^2)} \right)
\]

(10)

when the two fibers are properly aligned, the transverse and angular offset is zero, the eqs (7) and (9) reduce to eq. (5) and eqs (8) and (10) reduce to eq. (6) and therefore the splice loss will be the minimum. Further, the splice loss starts to increase with increasing values of \( u \) and \( \theta \).
IV. Simulation Results

The MFD of the SMF SMF-28e is about 10 μm. According to Fig. 1, the enlarged modefield of the PCF can match that of the SMF when the hole collapse ratio is 0.5 – 0.6. Figure 2(a) shows schematically how the hole collapse can lead to a change of the MFD of the PCF. As shown in Fig. 2(a), the PCF experiences a smooth transition after arc discharge because of the longitudinally decreasing temperature, which makes the holes collapse gradually along the fiber. As a result, the MFD of the PCF increases gradually from its original value to a value that can match with that of the SMF at the joint. The idea of realizing the MFD match by hole collapse has been
achieved by several methods. In general, both the outer diameter and the pitch shrink longitudinally, which is not desirable. Our method can provide a better control of the MFD of the PCF and yet does not lead to a significant change in the outer diameter. We simulate the splice between the SMF and the solid-core PCF with a full-vector beam propagation method (OptiBPM, Optiwaveinc.). The variation of the splice loss with the transition length at different collapse ratios at the wavelength 1550 nm are shown in Fig. 3(a). We find that the loss is lowest when the transition length is around 20 μm, which can be achieved with a collapse ratio in the range [0.457, 0.592], in agreement with the results shown in Fig. 1. We also calculate the spectral dependence of the loss. The results are shown in Fig. 3(b), which assumes a transition length of 21.6 μm and a collapse ratio of 0.293. The oscillations shown in Fig. 3(b) suggest that the MFD of the SMF and the PCF have different spectral dependences. Nevertheless, by properly controlling the hole collapse ratio and the transition length, it is possible to achieve a low splice loss over a wide wavelength range. For a hollow-core PCF, where light is confined in the central hole by the photonic bandgap effect, fusion splicing can easily destroy the bandgap structure of the fiber and introduce a large loss. To achieve a low splice loss, it is necessary to maintain the structure of the fiber as much as possible, which means that no air-hole collapse should be allowed, as shown schematically in Fig. 2(b). To confirm this, we simulate the splice between the SMF and the hollow-core PCF HC-1550-2 with OptiBPM (see Table 1 for the fiber parameters). The variation of the splice loss with the collapse ratio for different transition lengths at the wavelength of 1550 nm are shown in Fig. 4. The lowest loss occurs at a zero collapse ratio, i.e., when there is no hole collapse.
Fig. 2. The relationship between collapse ratio, $d/\Lambda$, and MFD for the solid-core PCF ESM-12-01, where the inset shows the dependence of the butt coupling loss on the collapse ratio.
V. Experiment Results

The Arc fusion splicer (FSM-60S) was set with typical parameters, a summarized list of these parameters were given in the table (1). The transmission power in SMF-28 at wavelength of 1550nm was measured by power meter and recorded output power to act as reference measurement (500µw).

| Prefusion time(ms) | 180 |
|--------------------|-----|
| Prefusion power STD (bit) | STANDARD |
| Gap(µm) | 15 |
| Overlap(µm) | 10 |

The experiment has been working in two ways, first splice losses as a function of the fusion time with the fusion power is fixed, and other splice losses as a function of the fusion power with the fusion time is fixed. The transmission power in (SMF-PCF-SMF) were measured by using light source of 1550nm wavelength and the losses were calculated by using the equation (9). The transmission power and Splice losses of optical fiber (SMF-28/PCF (ESM-12)/SMF-28) were given in tables (2) and (3) at fixed power STD-10 (bit) and STD+10 (bit) respectively.

| Arc Time (ms) | Arc power (bit) | Output power between two points(µw) | Total (α) Splice loss for two points(dB)/m | Coupling efficiency $\eta = \frac{P_{out}}{P_{in}}$ |
|---------------|-----------------|-------------------------------------|------------------------------------------|-----------------------------------|
| 1000          | STD-10          | 390                                 | 0.21                                     | 78%                               |
| 1500          | STD-10          | 370                                 | 0.26                                     | 74%                               |
| 2000          | STD-10          | 395                                 | 0.204                                    | 79 %                              |
| 2500          | STD-10          | 450                                 | 0.09                                     | 90 %                              |
| 3000          | STD-10          | 457                                 | 0.07                                     | 91.4%                             |
| 3500          | STD-10          | 369                                 | 0.28                                     | 72%                               |
| 4000          | STD-10          | 350                                 | 0.3                                      | 70%                               |

MFDs in SMF-28 and ESM-12 in PCF are equal, the overlap is (10 µw) , and Gap(15 µw) , the fusion power was fixed at STD - 10(bit) and varied the fusion time from (1000 to 4000) ms with a step of 500 ms.
The smallest losses (0.07dB/m) (0.09dB/m) were achieved when the Arc time was 3000 ms and 2500ms respectively at fixed Arc power (STD - 10(bit)), due to increase the temperature and decrease viscosity of SMF-PCF joint which will cause air- holes collapse of the PCF to degree that does not alter the mode field in PCF and mode field kept equal between two fibers, therefore a suitable Arc power and Arc time to soften the tips of the PCF and the SMF which is achieved a good mechanical strength of the joint, and minimize the collapse of air holes, so there is a trade off between splice loss and mechanical strength, when the fusion time less than (3000,2500 ms) the splicing losses are maximize due to low temperature and short air- holes collapse of the PCF which will cause weak splice joint which will easily break and bad mechanical strength between two fibers, when the fusion time more than (3000 ms) the splicing losses maximize due to high temperature and long air- holes collapse of the PCF which will cause mode field mismatching between two fibers.

Table (3) and figure (2) show that the fusion power was fixed at STD + 10(bit) and the variation of the fusion time from (1000 to 4000) ms with a step of 500 ms. The smallest splice loss (0.166dB/m) was achieved when the arc time was 3000ms due to increase temperature and decrease viscosity of SMF-PCF joint which will cause air- holes collapse of the PCF to degree that does not alter the mode field in PCF and mode field kept equal between two fibers, when the fusion time less than (3000 ms) the splicing losses maximize due to low temperature and short air- holes collapse of the PCF which will cause weak splice joint and leads to bad mechanical strength between two fibers, when the fusion time more than (3000 ms) the splicing losses maximize due to high temperature and long air- holes collapse of the PCF which will cause mode field mismatching between two fibers.

Figure (3) show that the corresponding splice loss for (0.387 dB/m) at fixed Arc power STD + 10(bit) and Arc time (1000) ms, figure (3) shows the air- holes collapse of the PCF is minimal and the splice loss is large (0.387 dB/m) due to low temperature, high viscosity. The fiber tips dose not reach to softening point and poor mechanical strength.

Fig (3): Microscope image of the splice zone loss between PCF (ESM-12) on the right, and the SMF-28 on the left. The collapsed length is ~98.488µm when the magnification power (40 X) at STD + 10(bit) and Arc time 1000ms.
Fig (4): Microscope image of the splice zone between PCF (ESM-12) on the right, and the SMF-28 on the left. The collapsed length is ~147.340µm when the magnification power (40 X) at STD - 10(bit) and Arc time (3000) ms.

VII. Conclusion

In conclude, OptiBpm software is powerful that can be used to create and investigate multi functions optical component and export them to optical simulation. Various parameters of optical properties and simulation can be altered easily and enhance more efficient investigation will be achieved. Splicing of HC-PCF, SC-PCF and SMF are introduced and different parameters effect such as transition length. Collapse ratio, MFD are investigated to optimize the overall performance of the resultant optical component. MZI based SMF and PCF are simulated and empirical splicing is conducted. This work shows that splicing process of SC-PCF can be optimized.
reduced with controlling the arc time and thus collapse ratio in addition to transition length. MZI of SC-PCF shows min. loss (0.01 dB). While HC-PCF splicing process should be matching as possible the collapse region which means proportional relation of MZIHC-PCF losses increasing with collapse ratio and transition length. Where simulation results of MZISC-PCF and SC-PCF losses are respectively. In general, splicing of MZI based on SC-PCF needs investigation splicing are time and power to find min. loss with respect to collapse ratio and transition length. Beside of that, MZI based on HC-PCF splicing process should exhibit min. collapse region and ratio.

References

I. A. D. Yablon and R. T. Bise, “Low-loss high-strength microstructured fiber fusion splices using GRIN fiber lenses,” IEEE Photon. Technol. Lett. 17(1), 118–120 (2005).

II. A. Ishikura, Y. Kato, T. Ooyanagi, and M. Myauchi, “Loss factors analysis for single-mode fiber splicing without core axis alignment,” J. Lightwave Technol. 7(4), 577–583 (1989).

III. A. Ortigosa-Blanch, J. C. Knight, W. J. Wadsworth, J. Arriaga, B. J. Mangan, T. A. Birks, and P. St. J. Russell, “Highly birefringent photonic crystal fibers,” Opt. Lett. 25(18), 1325–1327 (2000).

IV. B. Bourliaguet, C. Paré, F. Emond, A. Croteau, A. Proulx, and R. Vallée, “Microstructured fiber splicing,” Opt. Express 11(25), 3412–3417 (2003).

V. T. S. Mansour, and F. M. Abdulhussein, “Dual measurements of pressure and temperature with fiber Bragg grating sensors,” Al-Khwarizmi Engineering Journal 11(2), 86–91 (2015).

VI. G. E. Town and J. T. Lizier, “Tapered holey fibers for spot-size and numerical-aperture conversion,” Opt. Lett. 26(14), 1042–1044 (2001).

VII. G. Fu, W. Jin, X. Fu, and W. Bi, “Air-holes collapse properties of photonic crystal fiber in heating process by CO2 laser,” IEEE Photon. Jour. 4(3), 1028–1034 (2012).

VIII. J. C. Knight, “Photonic crystal fibres,” Nature 424(6950), 847–851 (2003).

IX. F. Q. Mohammed, and T. S. Mansour, “Design and Implementation Tunable Band Pass Filter based on PCF-Air Micro-cavity FBG Fabry-Perot Resonator,” Iraqi Journal of Laser. 18(1), 13–23 (2019).

X. J. H. Chong and M. K. Rao, “Development of a system for laser splicing photonic crystal fiber,” Opt. Express 11(12), 1365–1370 (2003).

XI. T. S. Mansour, and D. H. Abbass, “Chemical Sensor Based on a Hollow-Core Photonic Crystal Fiber,” Iraqi Journal of Laser. 12(A), 37–42 (2013).

XII. J. Lægsgaard and A. Bjarklev, “Reduction of coupling loss to photonic crystal fibers by controlled hole collapse: a numerical study,” Opt. Commun. 237(4-6), 431–435 (2004).
XIII. J. T. Kristensen, A. Houmann, X. M. Liu, and D. Turchinovich, “Low-loss polarization-maintaining fusion splicing of single-mode fibers and hollow-core photonic crystal fibers, relevant for monolithic fiber laser pulse compression,” Opt. Express 16(13), 9986–9995 (2008).

XIV. J. T. Lizier and G. E. Town, “Splice losses in holey optical fiber,” IEEE Photon. Technol. Lett. 13(3), 466–467 (2001).

XV. L. M. Xiao, M. S. Demokan, W. Jin, Y. P. Wang, and C. L. Zhao, “Fusion splicing photonic crystal fibers and conventional single-mode fibers: microhole collapse effect,” J. Lightwave Technol. 25(11), 3563–3574 (2007).

XVI. L. Xiao, W. Jin, and M. S. Demokan, “Fusion splicing small-core photonic crystal fibers and single mode fibers by repeated arc discharges,” Opt. Lett. 32(2), 115–117 (2007).

XVII. M. L. V. Tse, H. Y. Tam, L. B. Fu, B. K. Thomas, L. Dong, C. Lu, and P. K. A. Wai, “Fusion splicing holey fibers and Single-Mode Fibers: A simple method to reduce loss and increase strength,” IEEE Photon. Technol. Lett. 21(3), 164–166 (2009).

XVIII. P. J. Bennett, T. M. Monro, and D. J. Richardson, “Toward practical holey fiber technology: fabrication, splicing, modeling, and characterization,” Opt. Lett. 24(17), 1203–1205 (1999).

XIX. P. St. J. Russell, “Photonic-crystal fibers,” J. Lightwave Technol. 24(12), 4729–4749 (2006).

XX. R. Thapa, K. Knabe, K. L. Corwin, and B. R. Washburn, “Arc fusion splicing of hollow-core photonic bandgap fibers for gas-filled fiber cells,” Opt. Express 14(21), 9576–9583 (2006).

XXI. T. A. Birks, J. C. Knight, and P. S. Russell, “Endlessly single-mode photonic crystal fiber,” Opt. Lett. 22(13), 961–963 (1997).

XXII. Z. Xu, K. Duan, Z. Liu, Y. Wang, and W. Zhao, “Numerical analyses of splice losses of photonic crystal fibers,” Opt. Commun. 282(23), 4527–4531 (2009).