Optimization of the splice loss between photonic-bandgap fibers and conventional single-mode fibers

Kiarash Zamani Aghaie,* Michel J. F. Digonnet, and Shanhui Fan
Edward L. Ginzton Laboratory, Stanford University, 450 Via Palou Mall, Stanford, California 94305, USA
**Corresponding author: kzamani@stanford.edu*

Received February 12, 2010; accepted April 23, 2010;
posted May 17, 2010 (Doc. ID 124208); published June 2, 2010

To understand the loss limitations of a splice between a hollow-core fiber and a conventional fiber, we use a numerical model to calculate the expected coupling loss between the NKT Photonics' HC-1550-02 fiber and a single-mode fiber (SMF) of arbitrary step-index profile. When the SMF parameters are optimized, the splice loss is predicted to be as low as ~0.6 dB. This minimum is believed to be largely due to mode-shape mismatch. These predictions are confirmed experimentally by optimizing the splice loss between this photonic-bandgap fiber and five SMFs with different mode-field diameters (MFDs) and V numbers. With the SMF-28 fiber, the measured loss is 1.3 dB, in excellent agreement with theory. Using a SMF with parameters close to the optimum values (MFD $= 7.2\ \mu$m and $V = 2.16$), this loss was reduced to a new record value of 0.79 dB. © 2010 Optical Society of America

OCIS codes: 060.2270, 060.2300, 060.2390.

Photonic-bandgap fibers (PBFs) have been intensively studied in the past decade, and they have found numerous potential applications [1,2]. For most applications, it is critical to be able to splice a PBF to a single-mode fiber (SMF) with low loss, if only because most basic fiber components, particularly couplers, are made with SMF. Researchers have developed a technique to arc splice a hollow-core fiber (NKT Photonics' HC-1550-02) and Corning's SMF-28 fiber with a minimum loss of ~1.45 dB [1,3]. A lower splice loss of 1 dB has also been demonstrated by applying longitudinal pressure to these two fibers prior to applying the arc [4]. In contrast, a simple overlap calculation using a Gaussian mode approximation based on the mode-field diameter of the two fibers (~7.5 and ~10.4 μm, respectively) predicts that the butt-coupling loss should be 0.46 dB [3]. Although this 0.5 to 1 dB difference has been tentatively explained by differences in the mode shapes, there is still a need to conduct thorough simulations to explain this measured loss. It is also important to explore the possibility of achieving a lower splice loss by selecting a solid-core fiber with a mode-field diameter (MFD) better matched to that of the hollow-core fiber.

In this Letter, we use a numerical model previously reported [5] to calculate the exact fields of the HC-1550-02 fiber's fundamental mode, and with them we compute the expected coupling loss between this fiber and an arbitrary step-index SMF. This analysis predicts that, when the SMF parameters are optimized (MFD $\approx 7.25\ \mu$m and $V = 2.405$), the splice loss should be as low as ~0.6 dB. We confirm these predictions by optimizing the splice loss between this PBF and five SMFs with different MFDs and V numbers. With the SMF-28 fiber, we measured a loss of 1.3 dB, in good agreement with theory. Using a SMF with parameters close to the optimum values (MFD $= 7.2\ \mu$m and $V = 2.16$), we reduced the splice loss to 0.79 dB. This is the lowest value reported to date for a splice between a hollow-core and a solid-core fiber using an arc splicer.

The field transmission (t) and reflection (r) coefficients at a butt-coupled junction between a SMF and a PBF can be described in terms of the normalized vector electric and magnetic fields $\mathbf{E_i}$ and $\mathbf{H_i}$ of the HE_{11} mode of the SMF, and the corresponding fields $\mathbf{E_t}$ and $\mathbf{H_t}$ of the PBF's fundamental mode. These modes are normalized to carry 1 W power, or

$$\langle \mathbf{E_t} | \mathbf{H_t} \rangle = \frac{1}{2} \mathrm{Re}\left(\int \mathrm{d}A \left(\mathbf{E_t} \times \mathbf{H_t^*} \right) \cdot \hat{z} \right) = 1, \tag{1}$$

where A is the cross-sectional area of the fiber. A similar expression applies for the SMF mode. Neglecting coupling into higher-order modes of the PBF, the continuity of the transverse fields at the interface between the fibers imposes

$$(1 + r)\mathbf{E_{iT}} = t\mathbf{E_{tT}}, \qquad (1 - r)\mathbf{H_{iT}} = t\mathbf{H_{tT}}, \tag{2}$$

where the subscript **T** represents the transverse components. Solving Eqs. (2) with the use of Eq. (1) yields

$$r = \frac{\langle \mathbf{E_t} | \mathbf{H_i} \rangle - \langle \mathbf{E_i} | \mathbf{H_t} \rangle}{\langle \mathbf{E_t} | \mathbf{H_i} \rangle + \langle \mathbf{E_i} | \mathbf{H_t} \rangle}, \tag{3}$$

$$t = \frac{2 \langle \mathbf{E_t} | \mathbf{H_i} \rangle \langle \mathbf{E_i} | \mathbf{H_t} \rangle}{(\langle \mathbf{E_t} | \mathbf{H_i} \rangle + \langle \mathbf{E_i} | \mathbf{H_t} \rangle)}. \tag{4}$$

The power reflection, transmission, and loss of the connection are then simply given by $R = |r|^2$, $T = |t|^2$, and $1 - T$.

We applied this method to predict the loss of a butt-coupled junction between a SMF and the HC-1550-02 fiber. We used our C++ finite-difference frequency-domain numerical code based on a hexagonal Yee's cell [5] for calculating the fundamental-mode fields of this PBF. We modeled the cladding holes as hexagons with a width $d = 0.97\Lambda$, where $\Lambda = 3.8\ \mu$m is the period of photonic crystal; each corner of the hexagon was rounded with a circle of diameter $d_c = 0.6d$. The ring around the core was modeled as a dodecagon with a thickness of 0.015Λ [6]. These values were selected so that the modal properties predicted by the code, namely, the bandgap width (266 nm), the center-band wavelength (1600 nm), the fundamental-mode effective index (0.995), and the air-filling ratio (0.92), matched the measured values from the manufacturer [7]. The discretized electric and magnetic fields of the HE_{11} mode predicted for this index profile and the exact HE_{11} fields of a SMF of arbitrary index profile were then inserted into Eqs. (3) and (4) to compute the butt-coupling loss.

The solid curves in Fig. 1 depict the calculated dependence of the butt-coupling loss on the SMF's MFD. Since the MFD depends on the core diameter and either the numerical aperture or equivalently the V number, we expect the loss to depend on not only the MFD but also V, which is indeed the case. As expected, for a given V, the loss is worst for very small or very large MFDs, in which case the mode mismatch is large. Between these two extremes, the loss is minimum for a MFD of ~7 to ~7.25 μm, depending on the V number, which is close to the PBF's MFD (~7.5 μm). The minimum loss decreases with increasing V number, and it is lowest for the largest V number that ensures single-mode operation (2.405). This minimum is as low as ~0.6 dB, which is more than half the lowest loss reported to date for a conventional splice (1.45 dB) [3]. This residual loss is likely the result of mode-shape mismatch between the two kinds of fiber. Note also that for the SMF-28 fiber, the predicted loss is 1.29 dB, which is consistent with the reported minimum.

For comparison, we show as a dashed curve in Fig. 1 the loss predicted when the HE_{11} mode of the SMF is approximated by a Gaussian mode, an approximation that has been occasionally invoked in the literature. This approximation is convenient in that it produces a universal curve independent of the V number, and it yields the same general trend. However, it underestimates the splice loss by as much as a few tenths of dB in the vicinity of the minimum loss, the departure increasing with decreasing V number. One must, therefore, use the exact SMF fields to obtain accurate loss predictions, presumably because a Gaussian mode underestimates the fields in the wings, where the HE_{11} mode of a PBF exhibits ripples that affect the modal overlap. It is worth mentioning that if we neglect the mode-shape mismatch between the two kinds of fiber, from the 4% Fresnel reflection from silica to air, we would expect a splice loss of ~0.18 dB. This is the minimum achievable loss if a PBF is designed to have a fundamental mode that most closely matches the one of a SMF.

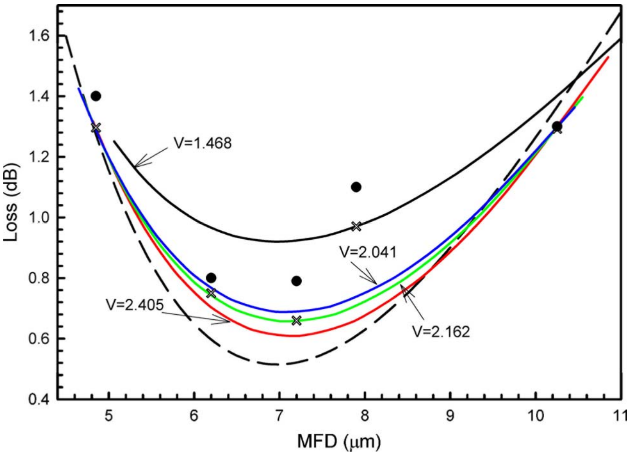

Fig. 1. (Color online) Calculated butt-coupling loss between a SMF and the HC-1550-02 hollow-core fiber versus the MFD of the SMF. Solid curves were calculated using the exact HE_{11} mode-field profiles of the SMF. The dashed curve was calculated using the Gaussian approximation of this mode. Filled circles represent the measured splice losses for different SMFs, and the cross under each circle identifies the theoretical curve corresponding to this particular fiber.

To confirm this theoretical dependence and demonstrate a splice with a significantly lower loss than reported to date, we arc spliced five SMFs with different MFDs to a 25 m spool of HC-1550-02 fiber. These fibers were the following: (1) Corning's SMF-28 (MFD $= 10.4$ μm); (2) Nufern's 980C-HP (MFD $= 7.8$ μm); (3) CorActive's PS-HNA-40 (MFD $= 6.2$ μm); (4) a specialty fiber from INO (MFD $= 4.9$ μm); and (5) Nufern's GF3 (MFD $= 7.2$ μm). We used a relatively long PBF to ensure that the higher-order modes were significantly attenuated at the output, so that we measured only the fraction of power coupled into the PBF's HE_{11} mode. The splicing technique and parameters were the same as in [3], except that we used a Fitel's S182PM splicer. Briefly, the splice plane was shifted horizontally from the electrodes by an offset of 50 μm (40 and 60 μm yielded nominally the same results). The arc time was set to 350 ms. For each SMF, splices were made with decreasing current settings. In general, the splice loss dropped as the current was decreased, but when the current was too low the splice became mechanically weak. The optimum current was thus chosen so as to produce a splice with the lowest possible loss while maintaining good mechanical strength. As reported by others [3,4], a high-quality cleave of the PBF was found to be paramount for achieving the lowest loss.

The minimum splice losses measured for each SMF are plotted as filled circles in Fig. 1; the cross underneath each circle identifies the loss curve pertinent to this fiber. The lowest loss we were able to obtain reproducibly was 0.79 dB (with the GF3 fiber). Measured and theoretical losses fall within ~0.12 dB of each other. This small difference might originate from (1) a slight difference in index profile between the actual and modeled fiber, (2) coupling to higher-order modes, and/or (3) a small deformation of the PBF. It should also be noted that the experimental error for the splice loss measurement is typically less than 0.1 dB.

It has been reported that in the other direction, i.e., when a short length of HC-1550-02 fiber is spliced into a SMF-28 fiber, the measured loss is often around 1 dB higher [1,3]. This apparent nonreciprocity is possibly due to the presence of higher-order modes in the PBF at the splice, which are filtered by the SMF-28 fiber and, thus, increase the measured loss. However, by using a long-enough PBF (25 m) in our measurements, we were able to obtain splices with reciprocal losses; the loss difference between the two directions was typically only ~0.1 dB.

In conclusion, modeling shows that the butt-coupling loss between the commonly used HC-1550-02 hollow-core fiber and a conventional SMF should be 1.3 dB for a SMF-28 fiber and as low as ~0.6 dB for a mode-matched SMF. This last value is believed to be due largely to mode-shape mismatch between the two types of fiber. We confirmed these predictions by optimizing the splice between this hollow-core fiber and SMFs with different MFDs and V numbers. The loss measured with the

SMF-28 fiber was 1.3 dB, in perfect agreement with theory, and the lowest loss observed with a closely mode-matched SMF is 0.79 dB, the lowest reported loss for such a splice using an arc splicer.

This work was supported by Litton Systems, Inc., a wholly owned subsidiary of Northrop Grumman Corporation.

References

1. R. Thapa, K. Knabe, K. L. Corwin, and B. R. Washburn, Opt. Express **14**, 9576 (2006).
2. M. J. F. Digonnet, S. Blin, H. K. Kim, V. Dangui, and G. S. Kino, Meas. Sci. Technol. **18**, 3089 (2007).
3. L. Xiao, M. S. Demokan, W. Jin, Y. Wang, and C. L. Zhao, J. Lightwave Technol. **25**, 3563 (2007).
4. M. L. V. Tse, H. Y. Tam, L. B. Fu, B. K. Thomas, L. Dong, C. Lu, and P. K. A. Wai, IEEE Photonics Technol. Lett. **21**, 164 (2009).
5. K. Zamani Aghaie, V. Dangui, S. Fan, M. J. F. Digonnet, and G. S. Kino, IEEE J. Quantum Electron. **45**, 1192 (2009).
6. R. Amezeua-Correa, N. G. R. Broderick, M. N. Petrovich, F. Poletti, and D. J. Richardson, Opt. Express **14**, 7974 (2006).
7. http://www.nktphotonics.com/side5334.html/HC-1550-02-091222.pdf.