Splice losses in holey optical fibers

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Abstract: Splice losses between standard step-index fiber and holey optical fibers were calculated for a range of fiber parameters and wavelengths using finite-difference time-domain simulations. The optimal holey fiber parameters for minimum splice loss were determined. It was found that the optimal parameters could also be predicted using analytical approximations incorporating the effective index model.

Holey optical fiber (HF) is an all-silica optical fiber with an array of longitudinal air holes providing the guidance mechanism.[1] They are an exciting innovation, as their strong guidance and numerous degrees of freedom in design provides the potential for realizing a range of novel fiber devices and applications not possible with standard step index fibers (SIF). However, to be widely useful HF's must be interfaced with minimal loss to a range of other optical waveguides and devices. Consequently it is important to determine the splice losses between HF and other waveguides, and if possible to optimize the HF structure to minimize splice loss. Loss for a particular SIF to HF splice has been measured experimentally at 1.5 dB,[2] however no detailed investigation of splice loss involving holey fibers has been conducted. Herein we report numerical calculations of splice loss between standard step index fiber and refractive index guiding HF with hexagonal symmetry, ie. in which the absence of a hole forms a core, and a hexagonal array of air holes, with diameter d and pitch Λ, forms a low effective-index cladding. We show that low splice losses should be possible, and propose an efficient design method to minimize these losses.

Early analyses of HF properties used the equivalent step index approximation, or effective index model,[3] or alternatively series expansion of the fields using localized basis functions.[4] More recently published models utilize other established methods such as the finite element method.[5] The latter approaches are restricted to modelling axially uniform fibers, though splice losses may be determined by evaluating the overlap integral of the calculated guided modes of the spliced fibers (eg. mode mismatch accounted for the loss in the experiment referred to above)[2].

We used finite-difference time-domain (FDTD)[6] simulations to calculate the transmitted and reflected fields in axially nonuniform waveguides. A substantially modified and significantly optimized version of publicly available software[7] was used to perform the FDTD simulations. A structure was defined containing short coaxial lengths of HF and a common SIF (SMF-28) either side of a butt joint between them (ie. the splice). A short pulse input with optical carrier at the wavelength of interest was directed towards the splice from the SIF with LP_{01} field distribution, calculated analytically.[8] The energies in the incident, transmitted and reflected waves were monitored to determine the splice loss. The cross sections at which the fields were monitored were kept at a large enough distance from the splice to avoid corruption by standing waves. Windowing techniques were used to separate radiated and guided field components (described in more detail in following sections). The numerical results so obtained were quite general with respect to direction of incidence, and polarization. Splice loss for incidence from the HF follows by reciprocity. The polarization modelled had the E field vector aligned with a pair of opposite inner holes of the HF, however any linear polarization is a superposition of this and its rotated degeneracies, and will thus exhibit the same splice loss.

Figure 1 shows the calculated incident and transmitted intensity distributions across the fiber for λ=1.55μm if splicing from SMF-28 SIF to HF with Λ=1.8μm and d/Λ=0.188.

The wavelength and HF parameters match those used in the experiment referred to earlier,[2] whilst the use of SMF-28 provides a slightly larger input mode. A contour plot of the transmitted intensity is shown in Fig. 2, and corresponds well to other calculations of the mode in this HF.[2] Typically, we calculated the electromagnetic fields using 32 bit arithmetic on an array of up to 150 by 150 points in the transverse directions, representing up to a 20μm square cross section, and with more than 600 points in the longitudinal direction. Six field components were calculated at each point.

Measurement of the splice loss from a transmitted field distribution such as that in Fig. 1 requires separation of the guided energy from the radiated energy, as the vast majority of losses from the splice are radiative rather than reflective. Due to the numerically intensive nature of FDTD calculations, only short sections (ie. approximately 30μm) of fiber could be modelled either side of the splice. It was apparent that this was sufficient distance for most radiation to separate from the core, but insufficient for radiation to escape the computational window. Consequently we used a windowing technique to separate the guided energy around the HF core region from the surrounding radiated energy to determine the loss. This approach could be expected to introduce some error in the loss calculation, ie. by including some radiative energy in the window and excluding some guided energy from the window. Nevertheless our results indicate that this error is small (ie. in the order of 10%), and that such errors were not important for design optimisation. For example, we calculated the splice loss in Fig. 1 to be 1.7dB, which compares well to the 1.5dB measured experimentally.[2] Furthermore, later results show clear trends in splice loss with variation in fiber parameters, in agreement with analytical approximations based on effective index theory.

FDTD calculations of splice loss were performed for a range of HF parameters (Fig. 3) and a range of wavelengths (Fig. 4). For comparison, these plots also show semi-analytic approximations of the splice loss, derived using the effective index model[3] for HF in which the effective normalized frequency V_{eff}, the effective index of the holey cladding, and the core radius $\rho \approx 0.64\Lambda$,[5] were substituted into standard analytical approximations for spot size (assumed Gaussian) and splice loss.[8] The values of V_{eff} were obtained using piecewise approximations to published plots[3] (adjusted for $\rho \approx 0.64\Lambda$),[5] so whilst the splice losses calculated semi-analytically are not expected to be accurate, it is nevertheless evident they provided a useful benchmark for comparison with numerical results, and parameter optimisation.

The plot of splice loss between SMF-28 and HF with $d/\Lambda = 0.35$ at λ=2.0μm (Fig. 3a) provides a good example. The FDTD simulations computed the lowest splice losses (ie. 0.2 dB) for the same HF pitch as the effective index model, i.e. between Λ = 8.0 to 10.0μm, where the mode field diameter is similar in both fibers. For smaller pitch values the HF mode is expected to be smaller than the SIF mode, and consequently the calculated splice losses larger. Here the losses calculated by FDTD simulations were larger than predicted by the effective index model, which may be attributed to the difference in shape of the SIF and HF modes, and to the limited accuracy of the analytical approximation in this range. For pitch values larger than 10.0μm the HF mode diameter is expected to be larger than in the SIF, and so larger losses were expected as shown in the analytic approximation, but were not observed in the FDTD results. We believe the latter discrepancy is a result of limitations in the FDTD modelling when coupling a small diameter mode to a larger mode; a larger propagation distance than was computationally available, or a discontinuity such as a bend, was required to remove the radiating fields from the core region. Observations of the transmitted intensity distributions from our simulations support the latter conclusion.

Analyses of splice loss variation with HF hole size (Fig. 3b) and wavelength (Fig. 4) followed similar trends and expectations, within the limitations described above. The FDTD model was also used to investigate splice loss due to axis offset in a SIF-to-HF splice (ie. with optimal HF parameters for minimum on-axis loss). Again the FDTD calculations followed expected trends, with the losses predicted by the FDTD simulations slightly larger than losses derived using analytic approximations incorporating the effective index model. Significantly, in all cases the optimal HF parameters determined by the FDTD calculations coincided with analytical approximations based on the effective index model. We therefore conclude that the effective index model provides an convenient tool to optimize HF parameters for minimum splice loss to step index fibers, but that numerical calculations, such as presented herein, are required to predict the actual loss.

We believe this to be the first reported use of a finite-difference time-domain model to analyze holey optical fibers. The model was used to determine splice losses between holey fiber and step index fiber for a range of fiber parameters; an important task in integrating holey fiber with existing technology. Our FDTD calculations indicate that optimal holey fiber designs can also be predicted using established splice loss theory incorporating the effective index model.

This work was supported by the Australian Research Council.

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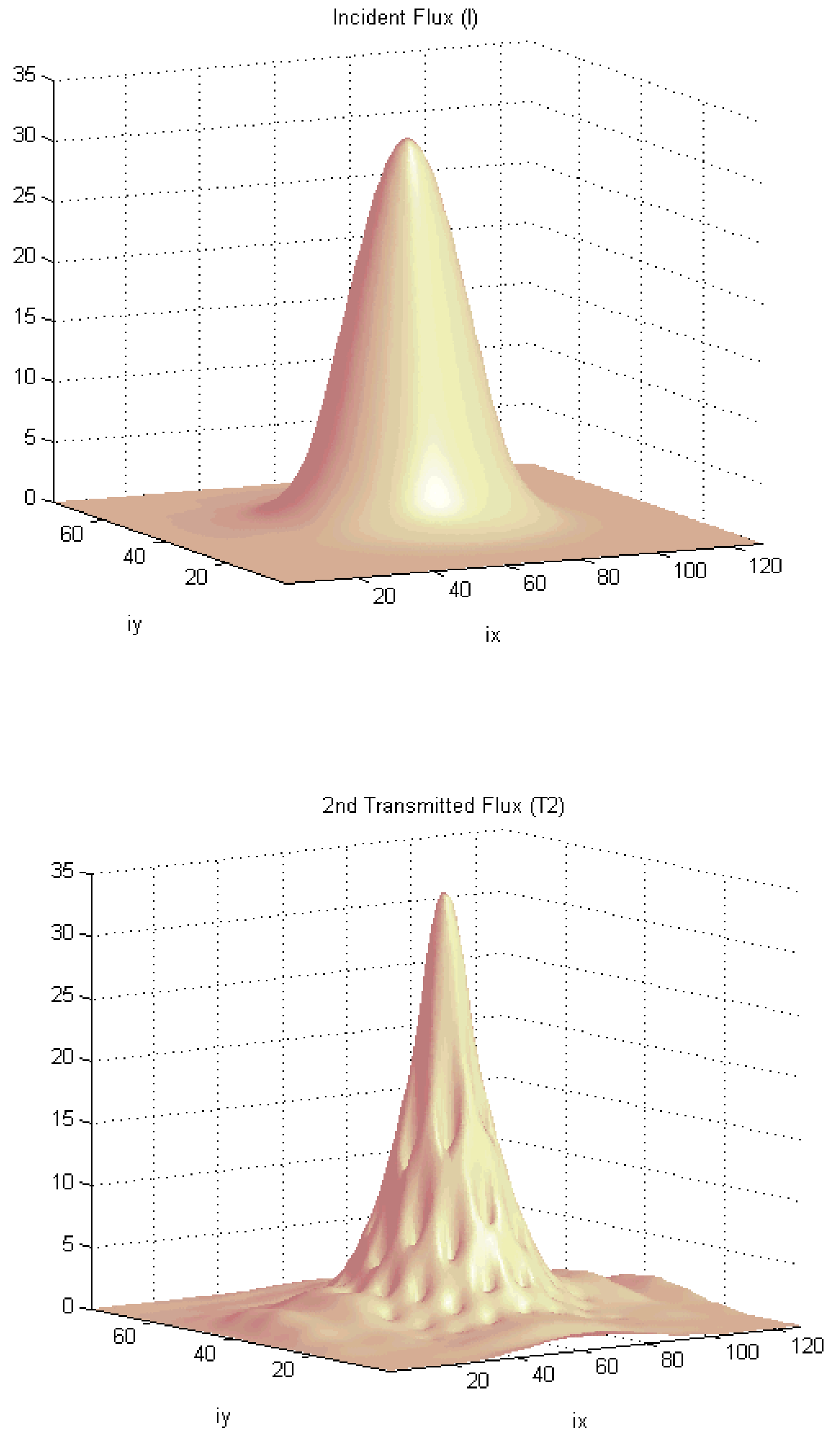


Fig. 1. (a) Intensity incident at λ=1.55μm from SMF-28 fiber and (b) transmitted in HF with Λ=1.8μm, d/Λ=0.188.

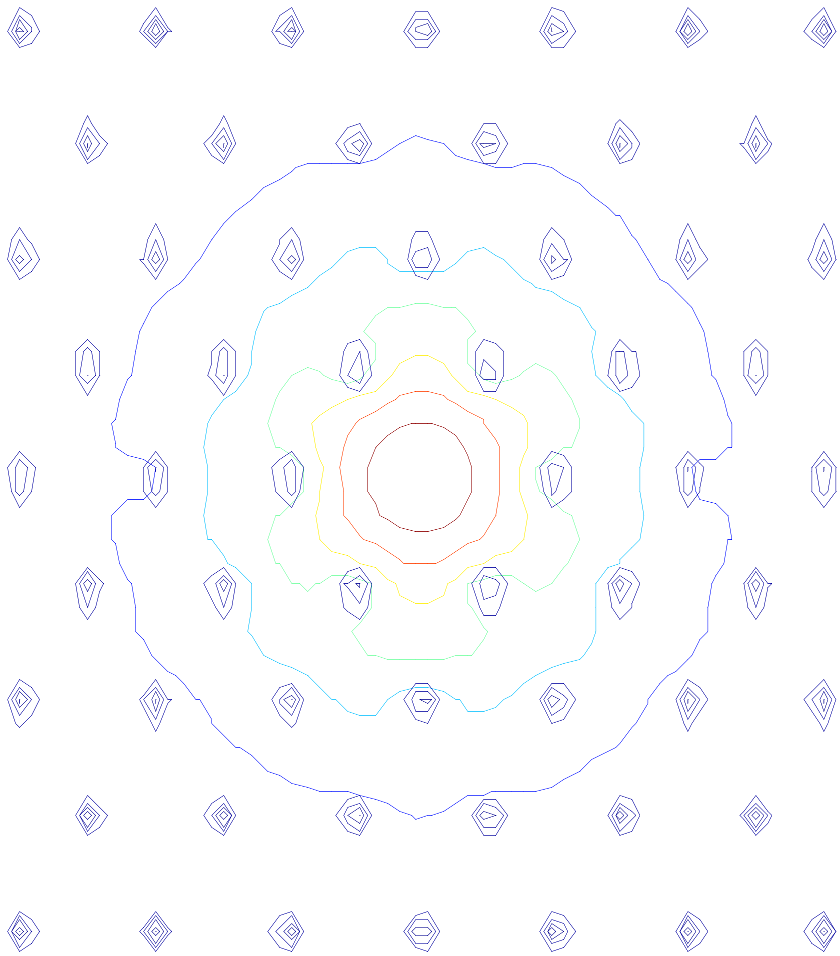
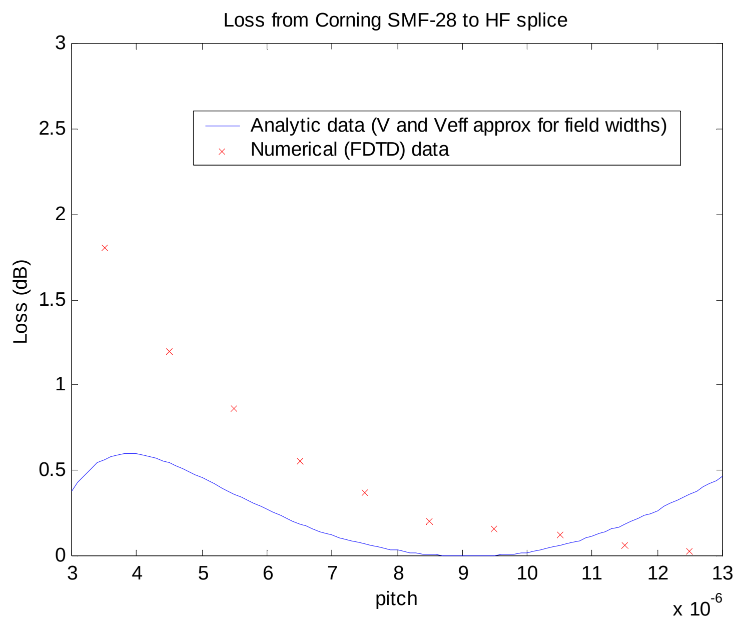


Fig. 2. Contour plot of the relative intensity in the HF, as per Fig1(b).



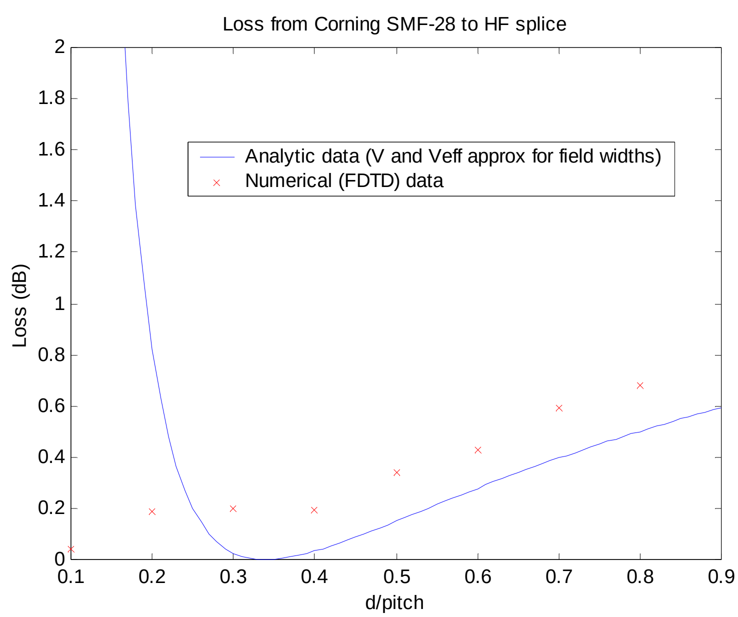


Fig. 3. Splice loss at λ=1.55µm for SMF-28 to HF with (a) d/Λ=0.35 at 2.0µm, and (b) Λ=6.56µm

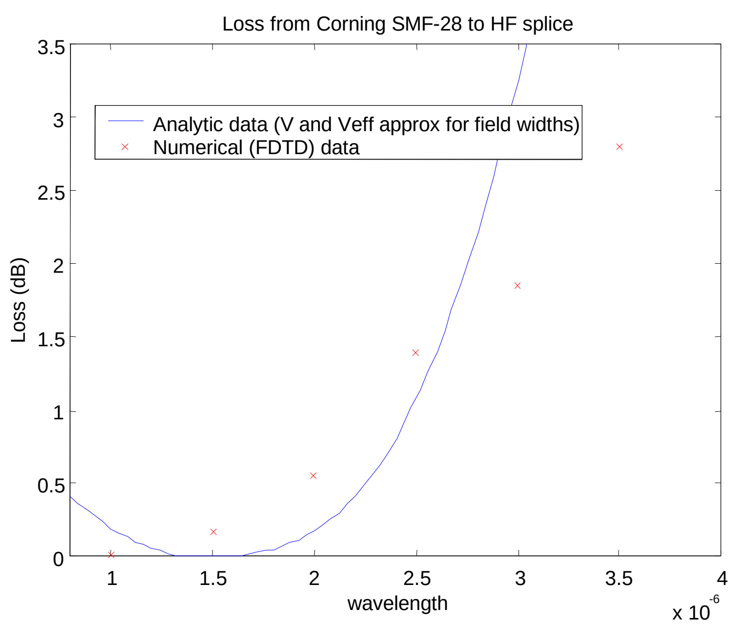


Fig. 4. Splice loss at λ=1.55μm for SMF-28 to HF with Λ=6.56μm and d/Λ=0.35.