Tapered holey fibers for spot-size and numerical-aperture conversion

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Adiabatically tapered holey fibers are shown to be potentially useful for guided-wave spot-size and numerical-aperture conversion. Conditions for adiabaticity and design guidelines are provided in terms of the effective-index model. We also present finite-difference time-domain calculations of downtapered holey fiber, showing that large spot-size conversion factors are obtainable with minimal loss by use of short, optimally shaped tapers. © 2001 Optical Society of America

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Holey optical fiber (HF) is an all-silica optical fiber with an array of longitudinal air holes providing the guidance mechanism.1,2 For guidance by total internal reflection, the regime of interest in this Letter, the absence of a hole forms a core and the surrounding array of air holes forms a low-effective-index cladding. HF exhibits a number of interesting properties that are not possible in standard step-index fibers (SIFs), including single-mode operation over an unprecedented range of wavelengths.3,4 It follows that at a single wavelength the size of a HF waveguide may be scaled by an appreciable factor and still remain single mode. The latter property is likely to be useful for tapered waveguide devices.

A major problem with SIFs is their inefficiency in coupling to integrated optical devices and waveguides, semiconductor devices such as laser diodes and other fiber waveguides with different properties. Coupling losses are caused by mismatch of the modal field distributions and by changes in effective index or wave impedance. A standard method of reducing coupling losses is to transform the guided mode by an adiabatic transition in waveguide structure (e.g., tapering) between the devices to be matched. The weak guidance provided in simple SIF tapers [i.e., with no coupling to the cladding mode4] and (or) lensing] usually results in multimode guidance or unacceptable loss before significant transformation of the guided mode can be achieved. Furthermore, the effective index of the guided mode confined to the narrow range determined by the core and cladding refractive indices.

In this Letter we show that adiabatically tapered HFs, shown schematically in Fig. 1, have the potential to perform substantial scaling and reshaping of guided mode-field distributions with low loss and without the problems associated with SIF tapers. We first discuss approximate design constraints on tapered HFs, in particular the adiabatic condition, in terms of the effective-index model of HFs.5,4 We then present finite-difference time-domain (FDTD) calculations of the guided mode in an optimally tapered HF structure, demonstrating significant changes in spot size and N.A. in relatively short tapers with minimal loss.

It has been shown that, if HFs are modeled in terms of SIF parameters, then (unlike for true SIFs) the effective normalized frequency parameter of the HF, \( V_{\text{eff}} \), does not scale linearly with the hole pitch or the size of the waveguide, as the effective index of a holey cladding is wavelength dependent.3,4 Consequently HF may be designed to remain single mode over an extremely wide range of wavelengths. Alternatively, for a fixed wavelength, the size of the waveguide could be scaled by an appreciable factor and still remain single mode. Interestingly, the N.A. of the HF waveguide and the effective index of the guided mode could also vary significantly for tapered conversion. For example, HFs with small filling factors \( d/\lambda \) could be used to increase the spot size from a typical SIF to a macroscopic scale. Alternatively, the strong confinement provided in HFs with larger filling factors could be used to substantially reduce the spot size from a typical SIF. By reciprocity, tapered HFs would be effective in both directions. The choice of HF parameters is constrained by the need to minimize losses (e.g., associated with both long and short cutoff wavelengths) and to avoid multimode behavior. Splice losses between the tapered HF and the SIF or other waveguides may also be minimized by appropriate choice of HF design parameters.10

Adiabatic tapering of waveguides refers to the gradual change of waveguide dimensions at a rate that minimizes losses caused by reflection and radiation. It is a well-known technique for achieving broadband impedance conversion and (or) scaling of modal field distributions with low loss. Ensuring adiabaticity in a HF taper is vital to minimizing losses in and (or) length of the taper. A criterion for adiabaticity in tapered SIF waveguides is that the angle of the waveguide boundary with respect to the direction of

Fig. 1. Schematic of the tapered holey fiber, scaled in size by D1:D2 over length \( L \).
propagation (i.e., the taper angle \( \theta_t \)) must be smaller than the local angle of diffraction of the guided beam, \( \theta_0 \) (i.e., \( \theta_t < \theta_0 \)).

Using the effective-index approximation\(^{24}\) and the Gaussian beam approximation for SIFs, one may express the diffraction angle in HF in terms of the HF parameters as

\[
\theta_0 = \frac{\lambda}{\pi \rho'} \ln \frac{V_{\text{eff}}}{\rho'},
\]

in which \( \rho' = 0.64A \) is used for improved accuracy of the effective-index model,\(^{12}\) \( \Lambda \) is the spacing of a hexagonal lattice of holes in the HF cladding, and \( V_{\text{eff}} \) is the effective normalized frequency parameter, given by

\[
V_{\text{eff}} = (2\pi \rho'/\lambda)\sqrt{n_{\text{eff}}^2 - n_{\text{cl}}^2},
\]

where \( n_{\text{cl}} \) is the effective index in the HF cladding and \( n_{\text{ef}} \) is the refractive index of the background material. Equation (1) is consistent with experimental measurements of the diffraction angle from HFs for the range of parameters tested.\(^{13}\)

We used Eq. (1) to investigate the adiabaticity, \( \alpha = \theta_0/\theta_t \), at each point along a variety of differently shaped HF tapers at specific wavelengths of interest. Conversely, we also used the criterion \( \alpha = \text{constant} \) to design optimally shaped tapers for specified wavelengths, end-to-end scalings, and HF parameters of interest. One constructs such tapers by starting at one end of the taper with defined hole pitch, \( \Lambda_0 \), and iteratively setting \( \theta_t = \theta_0/\alpha \) until the desired output pitch or end-to-end scaling has been reached. This process results in a taper of minimum length (i.e., with constant adiabaticity) for the specified parameters and also prescribes the taper shape that will provide the best performance if the taper is scaled to any other length.

Figure 2 shows an optimal downtaper with \( \alpha = 1.5 \), tapered from \( \Lambda_0 = 6.4 \) \( \mu \)m to \( \Lambda = 0.8 \) \( \mu \)m, and designed to guide a single mode at 1.55 \( \mu \)m. The fill factor \( d/\Lambda = 0.5 \) was chosen to give N.A. \( \sim 0.5 \) at the narrow end of the taper where the HF will be operating in the long-wavelength limit. The initial pitch, \( \Lambda_0 \), was selected to provide a good match to the guided mode in a single-mode SIF with core radius 3.84 \( \mu \)m and a N.A. of 0.15, and the final pitch was chosen to match an integrated optical waveguide. At the latter end of the taper, where \( V_{\text{eff}} < 1 \) and Eq. (1) could not be used, it was necessary to extrapolate the taper shape for a small distance from preceding values. Values used for \( V_{\text{eff}} \) in the taper design were obtained by use of piecewise approximations to published plots of \( V_{\text{eff}} \),\(^{4} \) adjusted for \( \rho' = 0.64\Lambda.\(^{12}\) With \( \alpha = 1.5 \) the resultant optimal taper was only 50 \( \mu \)m long; longer tapers with larger adiabaticity and better performance could readily be achieved in practice. Uptapers may be designed with a similar approach; however, the design constraints are different.

To evaluate the performance of the taper described above, particularly the spot-size scaling and taper loss, we used FDTD simulations of electromagnetic wave propagation in the axially nonuniform HF waveguide to determine the transmitted and reflected fields.\(^{10}\) We substantially modified and significantly optimized publicly available software\(^{9}\) to perform the FDTD simulations on a personal computer (i.e., a 666-MHz Pentium III, with 512-Mbyte RAM). Other published numerical modes that are capable of modeling tapered HF had prohibitive resource requirements (e.g., the finite-element method\(^{12}\)) and (or) made undesirable simplifying assumptions (e.g., the beam propagation method\(^{14}\)).

The exact structure defined in the FDTD model contained a short length of SIF that was butt-coupled (spliced) to a length of coaxial HF. The SIF, with known LP\(_{01}\) mode-field distribution,\(^{15}\) was used as a launch waveguide into the HF downtaper. A short pulse with an optical carrier at the wavelength of interest was directed toward the splice from the SIF. The HF section consisted of a uniform length at the initial pitch (where the incident fields were monitored), followed by the taper itself, then a uniform length at the final pitch (where the transmitted fields were monitored). The taper loss was approximated by use of a windowing technique to separate the fields associated with the guided mode in the HF core from surrounding unguided energy in the HF cladding. Because of the restricted computational power available, only the first few rings of holes in the HF were simulated; however, testing showed that simulating only a few rings had no significant effect on the results. The polarization of the launched LP mode had the electric field 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 loss from the taper. This assertion was validated for several cases.

Figure 3 shows the incident and transmitted intensity distributions in the HF taper calculated as described above, and with parameters as specified previously. The plots show a significant reduction in spot size of the guided mode, with an associated
We conclude that tapered HFIs have the potential to provide efficient coupling for a range of optical components, for example between standard step-index fibers and integrated or bulk optics. Using FDTD modeling, we demonstrated significant spot-size reduction in downtapered holey fiber, and from effective-index theory we also expected a significant increase in numerical aperture. By reciprocity we expect that uptapers will be similarly effective for spot-size expansion and numerical-aperture reduction. Furthermore, we expect similar conclusions to apply to any other waveguide with a periodic cladding structure.

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References