Tapered Holey Fibers for Spot Size and Numerical Aperture Conversion

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Abstract: 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 down-tapered holey fiber, showing that large spot size conversion factors are obtainable with minimal loss using short optimally shaped tapers.

Holey optical fiber (HF) is an all-silica optical fiber with an array of longitudinal air holes providing the guidance mechanism.[1] For guidance by total internal reflection, the regime of interest in this paper, the absence of a hole forms a core and the surrounding array of air holes a low effective index cladding. HF exhibits a number of interesting properties not possible in standard step-index fibers (SIF), including single mode operation over an unprecedented range of wavelengths.[2,3] It follows that at a single wavelength the size of an HF waveguide may be scaled by an appreciable factor and still remain single mode. The latter property is likely to be useful in 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, other fiber waveguides with different properties, etc. 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 (eg. tapering) between the devices to be matched. The weak guidance provided in simple SIF tapers (ie. with no coupling to the cladding mode,[4,5] and/or lensing[6]) 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 is confined to the narrow range determined by the core and cladding refractive indices.

In this letter we show that adiabatically tapered HF's, 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 firstly discuss approximate design constraints on tapered HFs, in particular the adiabatic condition, in terms of the effective index model of holey fibers[2,3]. We then present finite-difference time-domain[7,8] calculations of the guided mode in an optimally tapered HF structure, demonstrating significant changes in spot size and numerical aperture in relatively short tapers with minimal loss.

It has been shown that if HF's are modeled in terms of SIF parameters, then (unlike true SIFs) the effective normalized frequency parameter of the HF, V_{eff}, does not scale linearly with the hole pitch or size of the waveguide as the effective index of a holey cladding is wavelength dependent.[2,3] 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 numerical aperture of the HF waveguide and effective index of the guided mode could also vary significantly under tapered conversion. For example, HF's with small filling factors, d/Λ, could be used to increase the spot size from a typical SIF to a macroscopic scale. Alternatively, the strong confinement provided in HF's 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. Splice losses between the tapered HF and SIF, or other waveguides, may be minimized by appropriate choice of HF design parameters.[9]

Adiabatic tapering of waveguides refers to the gradual change of waveguide dimensions at a rate which minimizes losses due to 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 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 propagation (ie. the taper angle, θ_t) must be smaller than the local angle of diffraction of the guided beam, θ_0 (ie. $\theta_t < \theta_0$).[10]

Using the effective index approximation[2,3] and the Gaussian beam approximation for SIFs, the diffraction angle in HF may be expressed in terms of the HF parameters as

$$\theta_0 = \frac{\lambda\sqrt{\ln V_{eff}}}{\pi\rho'} \quad (1),$$

in which $\rho'=0.64\Lambda$ is used for improved accuracy of the effective index model,[12] Λ is the spacing of a hexagonal lattice of holes in the HF cladding, and V_{eff} is the effective normalized frequency parameter, given by

$$V_{eff} = (2\pi\rho'/\lambda)\sqrt{n_{co}^2 - n_{cl}^2} \quad (2),$$

where n_{cl} is the effective index in the HF cladding, and n_{co} the refractive index of the background material. Eq. (1) is consistent with experimental measurements of the diffraction angle from HFs for the range of parameters tested.[11]

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 α=constant to design optimally shaped tapers for specified wavelengths, end-to-end scalings, and HF parameters of interest. Such tapers are constructed by starting at one end of the taper with defined hole pitch, Λ_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 (ie. with constant adiabaticity) for the specified parameters, and also prescribes the taper shape that will provide the best performance if scaled to any other length.

Fig. 2 shows an optimal downtaper with $\alpha=1.5$, tapered from Λ_0 = 6.4μm to 0.8μm, and designed to guide a single mode at 1.55μm. The fill factor $d/\Lambda = 0.5$ was chosen to give NA~0.5 at the narrow end of the taper where the HF will be operating in the long wavelength limit. The initial pitch, Λ_0, was selected to provide a good match to the guided mode in a single mode SIF with core radius 3.84μm and NA=0.15, and the final pitch was chosen to match an integrated optical waveguide. At the latter end of the taper, where $V_{eff}<1$ and Eq. 1 could not be used, it was necessary to extrapolate the taper shape for a small distance from preceeding values. Values used for V_{eff} in the taper design were obtained using piecewise approximations to published plots of V_{eff},[2] adjusted for $\rho' = 0.64\Lambda$.[11] With $\alpha=1.5$ the resulting optimal taper was only 50μm long; longer tapers with larger adiabaticity and better performance could readily be achieved in practice. Uptapers may be designed using 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 finite-difference time-domain (FDTD)[7,8] simulations of electromagnetic wave propagation in the axially nonuniform holey fiber waveguide to determine the transmitted and reflected fields.[9] We substantially modified and significantly optimized publicly available software[8] in order to perform the FDTD simulations on a personal computer (ie. 666MHz Pentium III, with 512 Mbyte RAM). Other published numerical models capable of modeling tapered HF had prohibitive resource requirements (eg. the finite element method[12]) and/or made undesirable simplifying assumptions (eg. the beam propagation method[13]).

The exact structure defined in the FDTD model contained a short length of SIF butt-coupled (spliced) to a length of coaxial HF. The SIF, with known LP_{01} mode field distribution,[14] was used as a launch waveguide into the HF downtaper. A short pulse with optical carrier at the wavelength of interest was directed towards 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 using a windowing technique to separate the fields associated with the guided mode in the HF core from surrounding unguided energy in the HF cladding. Due to the restricted computational power available, only the first few rings of holes in the HF were simulated, however testing showed that this had no significant impact 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.

Fig. 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 associated increase in peak intensity, and good matching to the step index waveguide at the input. The loss was calculated to be approximately 0.3dB, and was derived from the results shown in Fig. 3 together with the reflected wave data, and includes the splice loss at the input.

We conclude that tapered HFs have the potential to provide efficient coupling between a range of optical components, for example between standard step-index fibers and integrated or bulk optics. Using FDTD modeling we have demonstrated significant spot-size reduction in downtapered holey fiber, and from effective index theory also expect a significant increase in numerical aperture. By reciprocity we expect 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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Fig. 1. Schematic of tapered holey fiber, scaled in size by D1:D2 over length L.

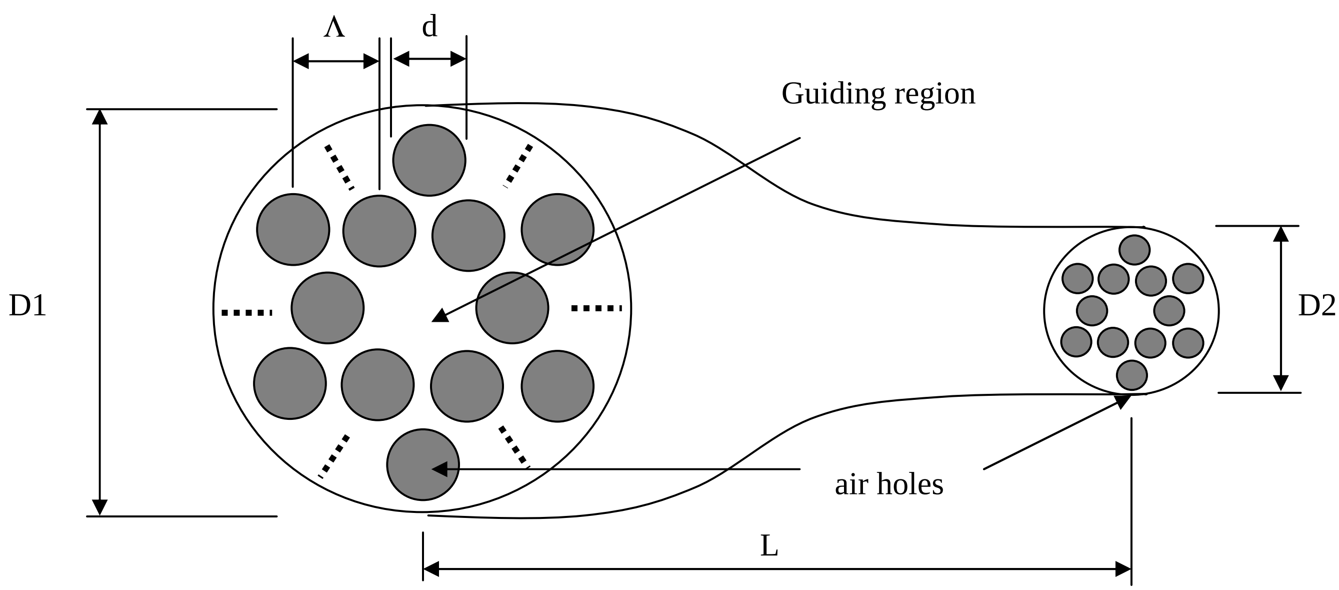

Fig. 2. An optimal adiabatic downtapered HF profile with α=1.5, scaled in size from Λ=6.4μm to 0.8μm over 50μm, designed using the method described in the text.

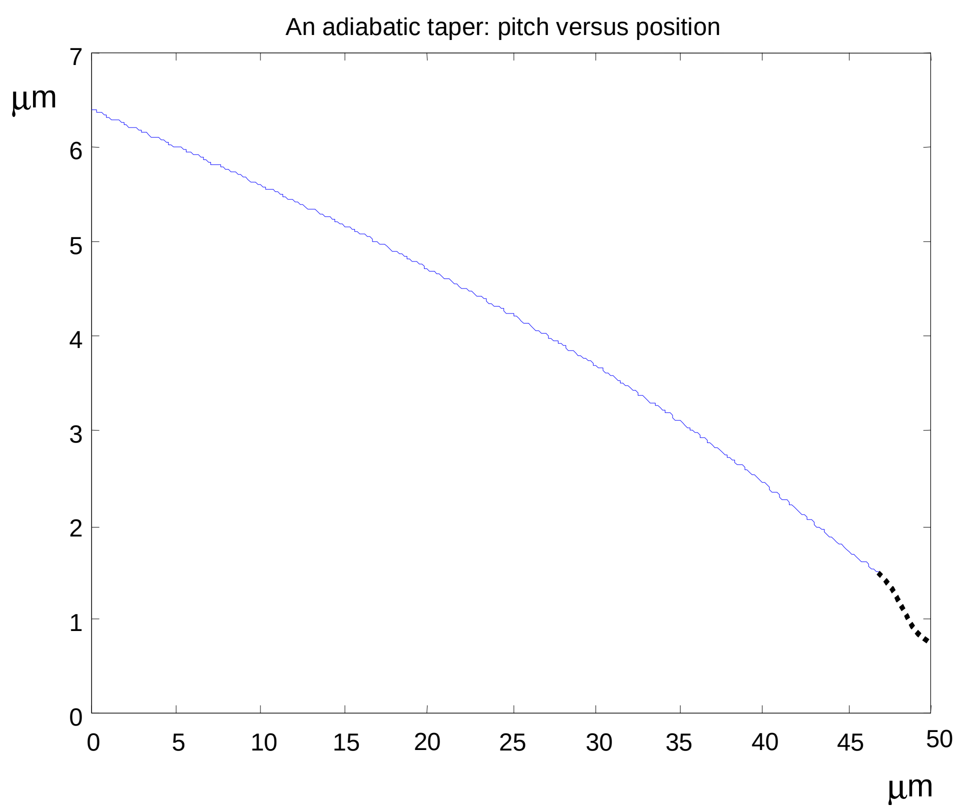

Fig. 3. a) Incident intensity (launched from SIF) in HF with Λ=6.4μm, and b) output intensity after 50μm adiabatic taper shown in fig. 2. The scales are normalized to peak input intensity.