Tapered holey fibers for spot size and numerical aperture conversion

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Abstract: Adiabatically tapered holey fibers are shown to be useful for guided-wave spot-size and numerical aperture conversion. Finite-difference-time-domain calculations are presented, detailing the performance of down-tapered holey fiber; large conversion factors are obtainable with minimal loss.

A major problem with standard step index fibers 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 mainly caused by mismatch of the modal field distributions, and partly by changes in wave impedance.

Adiabatic tapering of waveguides is a well-known technique for achieving broadband impedance conversion, and/or scaling of modal field distributions with low loss. However, tapering of standard step index fiber has limited uses; more than moderate scaling of the fiber dimensions, with proportional scaling of the normalized frequency, results in either multimode guidance or unacceptable radiation loss. Furthermore, the effective index of the guided mode will always be in the narrow range determined by the core and cladding refractive indices. These limitations are linked to the weak guidance that occurs in standard step index fibers.

It is known that holey fiber may be designed to remain single mode over an extremely wide range of wavelengths [1]. It follows that at a fixed wavelength the size of the waveguide may be scaled by an appreciable factor and remain single mode. Consequently adiabatically tapered holey fibers, shown schematically in figure 1, may be used to perform significant scaling of guided mode-field distributions with low loss. The effective index of the guided mode may also vary significantly.

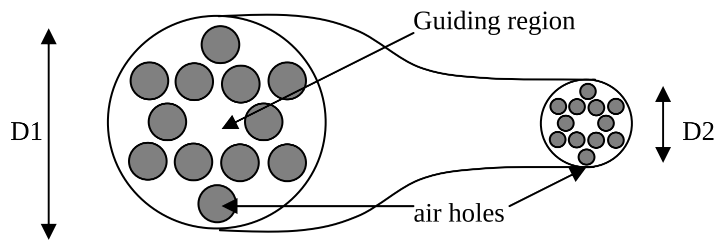

Fig 1. Schematic of adiabatically tapered holey fiber.

We have derived general guidelines for adiabatic taper design, and calculated the mode-field distributions at the both ends of an optimally shaped taper. The finite-difference-time-domain-method [2] was used to model the axially non-uniform tapered structures. Taper loss as a function of length was also calculated, and the results confirmed analytical constraints on the adiabaticity required for low loss [3].

For example, consider a down-tapered holey fiber to be used for matching a standard step index fiber to a laser diode or integrated optical waveguide. Using the equivalent step index approximation [1], it can be shown that to match the spot size of standard step index fiber (eg. SMF-28) at 1.55μm, the pitch of the holey fiber should be approximately Λ_1=6.5μm. We set the pitch at the narrow end of the taper at Λ_2=0.8μm, ie. to taper the spot size down by a factor of approximately 8. The fill factor was chosen to set the effective numerical aperture (NA) at the small end of the taper, which will likely be operating in the long wavelength limit. Here we set d/Λ=0.5; large enough to provide an effective NA~0.5, and small enough to maintain single mode guidance at the large end of the taper. To maintain good adiabaticity and low loss, it was determined that the taper should be longer than about

30μm [3], readily achieved in practice. Numerical results confirming the spot size reduction in the downtaper are shown in figure 2. The numerical results also showed that loss decreased with taper length, and became negligible for tapers longer than approximately 50μm. By reciprocity, uptapers are expected to perform similarly, however with different design constraints.

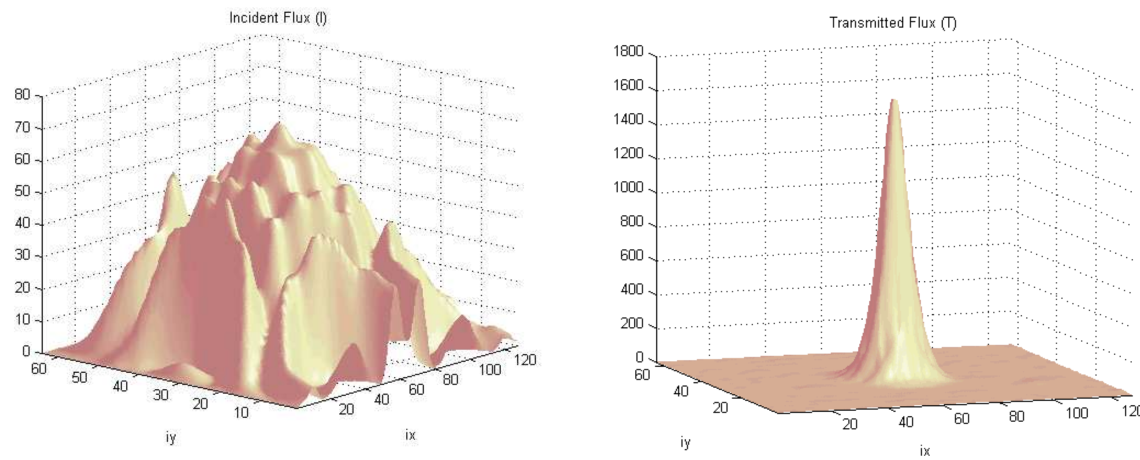

Fig 2. Calculated mode-field distributions at the input and output of a 50μm long down-tapered holey fiber with the following parameters: λ=1.55μm, Λ_1=6.4μm, Λ_2=0.8μm, d/Λ=0.5.

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[2] Taflov, A., Computational Electrodynamics: The Finite-Difference Time-Domain Method (Artech House, Boston, 1995)
[3] J.D. Love, "Spot size, adiabaticity and diffraction in tapered fibres", Electron. Lett. **23**, 993-994 (1987).