EFFECT OF TAPERING REALISTIC PHOTONIC CRYSTAL FIBER IN TAILORING BIREFRINGENCE AND DISPERSION PROPERTIES

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Abstract: The guiding properties namely, birefringence and dispersion of fabricated photonic crystal structures and their effects on adiabatic tapering of the structure are investigated using a finite difference mode convergence. Tapering, as an additional parameter, is seen to improve birefringence of a typical hi-bi PCF by one order magnitude. Our investigation with tapered PCF structures includes tailoring of dispersion properties and increase of nonlinearity which leads to more broadened and low threshold supercontinuum generation.

INTRODUCTION
Photic crystal fiber (PCF) offers highly tailorable modal properties namely, birefringence, group velocity dispersion, mode effective area, nonlinear parameters, for desirable and dedicated device applications due to its high flexibility in the designing of microstructured cladding. Along with the flexibility of designing transverse geometry of PCF, the tapering of such fibers also endow with significant enhancement of its transmission and waveguiding properties [1]. Tapered PCFs have interesting applications in bio-photonic sensors deploying its evanescent field properties. Mode conversion accompanied with pulse compression can be achieved using the technique of tapering down the PCF. Dispersion management i.e. tailoring of GVD is also achievable by tapering PCF that leads towards the low threshold supercontinuum (SC) generation and extension of broadband towards lower wavelengths. The experimental techniques for tapering of PCFs may require costly facilities and time-consuming steps. Therefore, a generic modeling tool for studying tapering effects of fabricated PCF structures are required to verify, sometimes to refine and map the target properties in a given application before their experimental realization. Such simulation algorithm then should facilitate in exploring new properties and also interpreting results obtained from experimental measurements. Keeping this in mind, we worked out a general recipe to model the tapering effects of fabricated PCFs of any arbitrary structures. We have investigated theoretically the guiding properties namely, birefringence and dispersion of fabricated photonic crystal structures and their effects on adiabatic/smooth tapering of the structure. During this analysis, it is assumed that the tapering process preserves transverse cross-sectional design and only shrinks its dimension. This consideration is firmly based on “fast & cold” adiabatic tapering [2] established in experimental tapering process of PCF. We apply our method of analysis on some well-known application-specific experimentally drawn structures that have appeared in the literature.

ANALYSIS METHOD
Modal analysis of the complex and arbitrary structure such as PCF has been a subject of research interest for the last two decades. In absence of any analytically tractable solution, several numerical and approximate methods have dealt with this problem. In this front, we reported a precise mode analysis technique of PCF structures using a finite difference mode calculation technique and detailed in [3]. In this work, for simulation of the tapered PCF structures, we implemented this scheme of mode analysis with the modification in the algorithm required to incorporate the effect of progressive tapering of the structure.

For modeling properties of fabricated (realistic) PCF structures, the index profile of the waveguide is determined from the SEM micrograph of the PCF cross-section by scaling it to the transverse dimension of the actual PCF. The RI profile \( n_2(x,y) \) is then placed over the computational domain for mode calculation. The process of tapering is simulated through a progressive reduction of the fiber’s cross-section in the discretized mesh preserving the shape and transverse geometry of the waveguide. Physically this fact corresponds to the adiabatic tapering. Numerically, starting with the calculated mode of the untapered structure as input field, the mode-field of the fiber having a small decrement in the cross-section of the structure is computed. This is repeated in each step of small cross-sectional reduction in a loop which could be looked upon as an evolution of the mode with reducing fiber diameter in a way the beam propagation yields. As a result, we determine a continuous variation of the mode-effective index in the dispersion curve and corresponding field distributions as a function of the tapered dimension of the structure. The mode analysis algorithm generates guided modes of the fiber both in scalar and semi-vectorial form.
NUMERICAL RESULTS

In order to check the validity and accuracy of our analysis method, we considered, as example cases, a few typical PCF structures well-known in the literature. The PCFs we selected for our case-study were experimentally studied with great success in terms of very high performance characteristics, namely, high birefringence, mode affective area, nonlinearity, dispersion, and SC generation. Also, the known results of experiments with these fibers facilitated us to illustrate quantitatively the influence of tapering the structures on the guided modes. In our work we also performed series studies on the effect of different tapered dimensions to improving the desired properties. In the following we discuss these characteristics and typical results pertaining to our analysis.

Birefringence

The PCF designing technology has been able to introduce significantly high degree of birefringence and a number of PCF structures are reported to have exhibited birefringence of \( \sim 10^{-3} \). However, tapering the PCF structure introduces additional birefringence because of the uneven flaring of the mode-field along the orthogonal axes across the cross-section. We studied this effect of changing birefringence of hi-bi PCFs with tapering. As a first case, we have computed the results of tapering of a typical hi-bi PCF [4] which was used as temperature sensor. We calculated the transverse index distribution of the PCF from its SEM micrograph (shown in inset of Fig.1) and then we determined its modal properties. The birefringence of this PCF has been obtained as \( 8.47 \times 10^{-4} \) at \( \lambda = 1.55 \) µm in its original (untapered) form. Introducing a progressive tapering into the structure we calculated the effect as a function of the tapered dimension using our analysis. As the tapering increases, the mode-field spreads more and more into the cladding as evanescent wave thereby increasing the birefringence. However, eventually a point is reached when the birefringence does not improve, rather becomes less because of the negligible core-guidance of the corresponding mode. In this process, a limiting value of improved maximum birefringence is achieved in the given PCF at \(~ 50 \%\) tapering of its original structure. With the influence of this amount of tapering on guided polarized modes, a birefringence \(~ 5.00 \times 10^{-3}\) has been obtained, which is one order of magnitude improvement. The result of this calculation is depicted in Fig.1, where the birefringence as a function of the tapered cross-section is plotted. It can be seen from this figure that the birefringence initially increases and then starts decreasing with a maximum around 50\% of the taper. This is a useful observation that yields a before-hand data towards experimental taper drawing.

We report our studies on another fabricated hi-bi PCFs with two-fold rotational symmetry [5]. Its SEM micrograph is shown in the inset of Fig.2. Using our analysis technique, we obtain the birefringence of this structure is \( 3.7 \times 10^{-3} \) at \( \lambda = 1.54 \) µm. While simulating the tapering process, the structure is seen to support guided modes till the tapering is \(~ 15\%\) and at this tapered dimension it almost doubles its birefringence from the original one. Figure 2 depicts the increase of birefringence as a function of tapering dimensions. We observed that the birefrigence start to decrease when the guided field goes to evanescence. This effect of flaring the guided modal field due to tapering can be clearly seen from the evolutions of fields in the structure. The extent of evanescent field due to tapering is seen to depend on the structural geometry, air-filling fraction and the operating wavelength.
Dispersion tailoring

As an integral part of the study, we have investigated the effect of tapering on the dispersion properties of PCFs. To show the validity of our method, we have compared the dispersion results obtained for the fabricated structure of [6] under tapering conditions with those reported results in [7].

Originally the PCF structure with 3.1 µm core diameter is treated to calculate the zero-dispersion wavelength (ZDW), \( \lambda_0 \), which is obtained as 850 nm. When it is tapered down to a diameter of 1.1 µm and 0.9 µm, the zero-dispersion wavelengths, \( \lambda_0 \) are obtained as 580 nm and 540 nm respectively. Thus, our calculated results closely match with the quoted results of [7] for the given amounts of tapering of the fibers. Figure 2 depicts this dispersion result calculated using our proposed method. Thus, this study confirms the efficacy of our technique for analysis of tapered realistic PCFs structure.

CONCLUSION

In this article, we have presented a method of simulating the tapering effect of PCFs using a finite difference analysis and demonstrated the enhancement or tailoring of the modal properties of fabricated air-silica PCF structure using tapering as a parameter. We analysed the effect for a few fabricated PCF structures reported in the literature using the micrograph image of PCFs that provided the transverse RI profiles. The scaled dimension of the structure is then modified proportionately to simulate the gradually tapered dimensions of the fiber in a finite difference computational environment of mode calculation. The obtained results show improved birefringence of hi-bi PCFs caused by tapering. The analysis also determines the extent of tapering of the structure to achieve a desired level of its evanescent field which has promising applications in evanescent field sensing technology. We showed that the dispersion properties of PCFs can be tailored by tapering, using some example PCFs. The reduced mode effective area on tapering and the resulting enhanced nonlinearity of PCF leads to generate low threshold supercontinuum in PCFs and establishes the possibility of wider and low threshold broadband source. Evidently, the results obtained from our investigation indicate an improvement in the overall characteristics and motivates exploring potential applications of PCF through such tapering. The analysis algorithm will therefore be a ready tool for estimating properties of a realistic arbitrary structure PCF with regard to the effect of tapering or progressively reducing dimensions of the structure.

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