Computational Electromagnetics Applied to Design and Modeling of Photonic Crystal Fibers

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Computational electromagnetics has become an essential tool in modern microwave and lightwave technologies, and many successful numerical methods have been proposed since its birth. In this paper a full-vector finite-element method is introduced to design and modeling of photonic crystal fibers which have attracted much interest recently mainly because of their unique properties.

Keywords : computational electromagnetics

1. Introduction

Photonic crystal fibers (PCFs) have attracted much interest recently mainly because of their unique dispersion properties. Light confinement is explained by two different mechanisms: the index-guiding effect and the photonic bandgap effect. Index-guiding PCFs, especially, also called holey fibers (HFs), with multiple air holes periodically arranged around the core possess numerous unusual properties, such as a wide single-mode wavelength range and great controllability in chromatic dispersion, modal birefringence, mode area, and nonlinearity.

To model PCFs accurately, especially with large air holes, it is crucial to use a full-vector model. In particular, a complete vector model is necessary for predicting sensitive quantities such as dispersion and birefringence. So far, various analysis methods have been developed for the design and modeling of HFs and photonic bandgap fibers, such as the effective-index approach, the plane-wave expansion method, the localized-function method, the multipole method, the finite-element method (FEM), the beam propagation method, and the finite-difference time-domain method. Each of these methods might be superior, with respect to reliability, efficiency, and/or accuracy for usual PCFs with six-fold rotational symmetry. The geometries of fabricated PCFs are, however, necessarily slightly disordered from perfect hexagonal symmetry, resulting in a slight polarization-mode dispersion that is one of the major sources of limitation in high-bit-rate optical transmission systems. The FEM is very useful not only for idealized-model simulations but also for real-model simulations based on actual fiber structures⁽¹⁾⁻⁽⁴⁾.

In this paper a full-vector FEM is applied to investigating the chromatic dispersion and modal birefringence, focusing on fabricated HFs. Through real-model simulations the polarization-dependent dispersion, which has been very often observed experimentally, is theoretically confirmed.

2. Simulation Results

The cross section of a HF fabricated by Hasegawa *et al.*⁽⁵⁾ is shown in Fig. 1. Figures 2(a) and 2(b) show, respectively, an image generated from the scanning electron micrograph

photograph in Fig. 1 and the element division, where the number of curvilinear hybrid edge/nodal elements is 16,000 and the degrees of freedom (DOF), which stand for the unknown electric-field variables used in the entire analysis region, $\text{DOF} = 110,000$. The transverse-electric-field vector distributions of slow-axis and fast-axis modes are, respectively, shown in Figs. 2(c) and 2(d). Figures 3(a) and 3(b) show, respectively, the dispersion and the birefringence. This fiber exhibits strong polarization-dependent dispersion and large birefringence of the order of 10^{-3} . The calculated dispersion for the fast-axis mode is in good agreement with the measured dispersion⁽⁵⁾. A large positive dispersion of $168 \text{ ps}/(\text{km}\cdot\text{nm})$ with a negative dispersion slope of $-0.044 \text{ ps}/(\text{km}\cdot\text{nm}^2)$ is obtained experimentally at $1.55 \mu\text{m}$ ⁽⁵⁾. A dispersion of $168 \text{ ps}/(\text{km}\cdot\text{nm})$ with a dispersion slope of $-0.09 \text{ ps}/(\text{km}\cdot\text{nm}^2)$ is numerically predicted at $1.55 \mu\text{m}$. Such dispersion properties would be unattainable by conventional fibers and valuable for dispersion compensation⁽⁵⁾. In Fig. 3(a) the polarization-independent dispersion for the corresponding idealized structure is also plotted, where the hole pitch $\Lambda = 1.8 \mu\text{m}$ and hole diameter $d = 1.6 \mu\text{m}$ ⁽⁵⁾.

3. Conclusion

A full-vector finite-element method has been successfully applied to investigating birefringence and dispersion in holey fibers. Through real-model simulations the polarization-dependent dispersion in actual fiber structures has been

Fig. 1. Scanning electron micrograph photograph of HF⁽⁵⁾

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(a)

(b)

(c)

(d)

Fig. 2. (a) Holey fiber with three rings of arrays of air holes, (b) example of an element division and the transverse-electric-field vector distributions of (c) slow- and (d) fast-axis modes⁽⁴⁾

(a)

(b)

Fig. 3. (a) Dispersion and (b) birefringence in the holey fiber with three rings of arrays of air holes⁽⁴⁾

numerically demonstrated.

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