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Study on polarization properties of twin-hole poling optical fibers

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ABSTRACT

Polarization properties of metal-filled twin-hole poling optical fiber are systematically investigated in this paper. Propagation and polarization dependent losses (PDLs), modal birefringence and the chromatic dispersion of the poling fiber with various fiber configurations are analyzed in detail. We revealed that a single polarization poling fiber with a length of a dozen centimeters could provide a high PDL (beyond 30 dB) and a low propagation loss (in the order of 1 dB). The choice of electrode material plays an important role for optimizing PDL and propagation loss of poling fiber. Holes with a large radius could effectively reduce the propagation loss of *y*-polarization while propagation loss of *x*-polarization mode remains approximately unchanged. The results, especially the polarization dependent characteristics are of significance for twin-hole fiber poling and applications of poled fiber devices.

1. Introduction

Glass based materials are widely used in modern electro-optics and optical fiber communications because of their excellent optical properties, such as low cost, low loss, high optical damage threshold, stable physical properties, etc. Due to the macroscopic inversion symmetry of such amorphous media, even-order nonlinear susceptibility are forbidden, limiting the application of glass based materials in second-order nonlinearity (SON). In 1991, Myers et al. first reported a large, permanent second-order nonlinear susceptibility ($\chi^{(2)}$) that reached 1 pm/v and can be created by thermal poling [1]. After that, intense research attention has been drawn to investigate the spatial distribution and the mechanism of $\chi^{(2)}$ in fused silica [2–5] and optical fiber [6–8]. Whereafter, poled optical fiber devices have been widely used in electro-optic (EO) modulators, electro-optical fiber switch, wavelength converter, second harmonic generation, optical parametric oscillator [9,10] and generation of entangled photons [11].

Due to low splicing and propagation loss, long interaction distance and the special structure can effectively avoid voltage breakdown, twin-hole fibers have been widely used in fiber thermal poling experiments and the aforementioned poled fiber applications. The spatial distribution and magnitude of induced SON are determined by external electric field, temperature, time, chemical composition and the fiber structure in thermal poling process [12–14]. For thermal poling twin-hole optical fiber, two methods of implanting the electrodes have been most frequently reported. One is inserting the metal wires ($\sim$10 μm radius) into the air holes from side-polished openings in the fiber while leaving an air gap between the electrodes and the holes [15]. Another is pumping the low melting alloys into the holes from the end of the fiber, filling up the entire cross section of the holes without air gap [16]. This paper focuses on the polarization properties of poling fiber with melting electrodes, since currently this configuration are generally used in thermal poling fiber. In terms of the SON characteristics, a close edge-to-edge distance between core and hole would be better for the SON overlapping fiber core [17]. However, a casual choice of this distance will cause great propagation loss due to the metal/alloy electrodes [16–18] and limit the practical application of poled fiber. It should be noticed that the size and distribution (distance and symmetry) of the holes, materials of the electrodes and the electrodes forms (melting or inserting electrodes) simultaneously affect the polarization properties of the poling fiber, such as propagation loss, modal birefringence, polarization dependent loss, dispersion, etc. Moreover, the fiber configurations affect the effectiveness of the introduced SON and the performance of the poled fiber based devices.

So far, research works have been conducted to investigate the effects of inserting metal electrodes in fibers and high extinction ratios have been demonstrated while most of them are conducted by changing the lattice structure [19], the number and position of electrodes in photonic crystal fiber [20] or the metal layer thickness in three-hole microstructured optical fiber [21] and D-shaped fiber [22], However, most of the results are demonstrated with the fiber configurations fixed. The high polarization dependent loss generally accompanied with high propagation loss which limits

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the application of poled fiber based devices. Propagation loss of twin-hole poling fibers with inserted electrodes has also been investigated, it is found that the loss of y-polarization mode is far lower than that of x-polarization mode and the fiber with inserting metal wires has better loss performance than the one with injecting melting alloys [23]. However, the results are calculated by an equivalent refractive model, in which the twin holes and the metal wires were approximated as a plane waveguide. Polarization properties are of significance for poled fiber based devices. Poled twin-hole fibers with high polarization dependent loss, low propagation loss and effective introduced SON in the core region are promising for a wide range of applications and to our best knowledge have not been presented until now. In addition, the relative permittivity of electrode material significantly influence on polarization properties of poling fiber.

For the purpose of keeping desirable overlap of SON over core region as well as polarization properties of poled fiber devices, systematic study of the effect of fiber configurations on polarization properties is extremely important. In this paper, we have analyzed polarization properties, including propagation losses, modal birefringence, polarization dependent losses and chromatic dispersion by performing simulation with different edge-to-edge distances between core and hole, radius of the hole, asymmetry of twin-hole and the permittivity of electrodes materials. The detailed results provide theoretical foundation for twin-hole fiber fabricating and the application of poled fiber based devices.

2. Theoretical calculation of twin-hole poling optical fibers

In our studies, the polarization properties of poling fiber are investigated by finite element method, a perfectly matched layer accompanied with a perfect magnetic conductor is used to truncate the computational domain. Fig. 1 shows the diagram of twin-hole optical fiber with melting electrodes, in which '+' and '−' represents the anode and cathode hole, respectively. The radius of fiber core and cladding are respectively taken from standard single mode fiber G.652 which are 4.1 μm and 62.5 μm. R (15–20 μm radius) represents radius of hole. The relative refractive index difference between fiber core (Ge doped) and cladding is $\Delta=4‰$. The edge-to-edge distance between core and anode hole and cathode hole are denoted as d_1, d_2, and are collectively referred to as d when $d_1=d_2$.

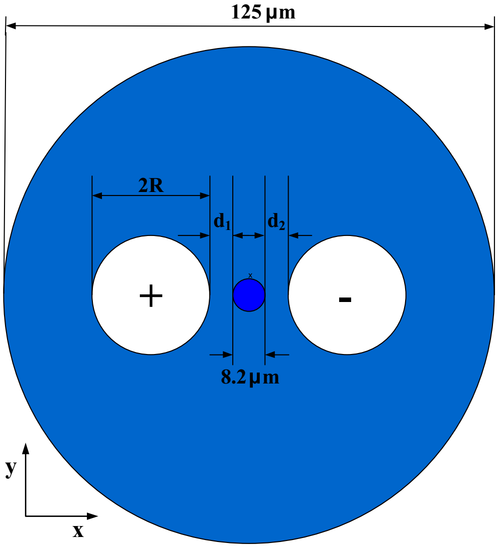

Fig. 1. Diagram of twin-hole optical fiber.

Refractive indices of fiber cladding (SiO$_2$) were obtained by the Sellmeier dispersion model. The complex relative permittivity of metal electrodes was obtained by the Lorentz–Drude (LD) dispersion model which can be described by the following equations [24]:

$$\hat{\varepsilon}_r(\omega)=\hat{\varepsilon}_r^{(f)}(\omega)+\hat{\varepsilon}_r^{(b)}(\omega), \tag{1}$$

$$\hat{\varepsilon}_r^{(f)}(\omega)=1-\frac{\Omega_p^2}{\omega(\omega-i\Gamma_0)}, \tag{2}$$

$$\hat{\varepsilon}_r^{(b)}(\omega)=\sum_{j=1}^{k}\frac{f_j\omega_p^2}{(\omega_j^2-\omega^2)+i\omega\Gamma_j}, \tag{3}$$

where $\Omega_p=\omega_p(f_0)^{1/2}$, ω_p is the plasma frequency, ω_j is the resonance frequency, f_j is the oscillator strength and Γ_j is the damping in time.

3. Results and discussions

Compared with standard single mode fiber (G.652), the propagation modes appear to be readily influenced by the lossy metal electrodes due to the introduction of electrodes in fiber's cross-section. Hence, polarization properties of poling fiber are in relevance with edge-to-edge distance between core and hole d, radius of the holes R, asymmetric distribution of the holes and permittivity of electrodes materials.

3.1. Edge-to-edge distance between core and hole d

For twin-hole poling optical fibers, there is a difference in effective index of fundamental mode of x-polarization mode (HE$_{11x}$) n_x and y-polarization mode (HE$_{11y}$) n_y due to asymmetric distribution in x- and y- direction in fiber's cross section (as shown in Fig. 1), in contrast to standard single mode fiber which the HE$_{11x}$ and HE$_{11y}$ modes are degenerate. For a better comprehension, we illustrated the power flow distribution around twin-hole fiber core as shown in Fig. 2. It is clear that a considerable fraction of power of HE$_{11x}$ mode concentrates on electrodes' surface, while that of HE$_{11y}$ mode is relatively normal. This observation results in the difference of HE$_{11x}$ and HE$_{11y}$ modes as well as polarization properties.

A pair of Ag electrodes is adopted in simulation with LD dispersion model parameters shown in Table 1. The difference in real part of n_x and n_y determines modal birefringence which is defined as $B=\mathrm{Re}|n_x-n_y|$. We show modal birefringence of the poling fiber at 1.31 μm and 1.55 μm wavelength as a function of d in Fig. 3. B drops roughly exponentially with the increase of d. This result is basically in accordance with the result in D-shaped fiber with gold coated on the flat surface in which the birefringence decrease with the distance from the fiber center to the flat surface increases [22]. At wavelength $\lambda=1.55$ μm, B decreases from 5.19×10^{-4} to 3.34×10^{-7} with d ranges from 1.9 μm to 10.9 μm. It is found that for the birefringent fiber, the fast axis is along the x axis, while the slow axis is along the y axis. We believe modal birefringence is ascribed to geometrical birefringence, and the influence of fiber structure which are asymmetric in x- and y-directions on mode field (mainly concentrated in fiber core) decreases with the increase of d. In addition, compared with B at wavelength $\lambda=1.55$ μm and 1.31 μm, longer wavelength exhibits higher birefringence due to the expansion of modal field. The detailed description of birefringence vary as a function of wavelength is shown in Fig. 4, where d is fixed as $d=4.9$ μm. We notice that B increases monotonically from 2.92×10^{-6} to 8.48×10^{-5} with wavelength increases from 1.2 μm to 1.7 μm.

As shown in Fig. 5, the lossy metal electrodes will bring additional propagation loss with $R=20$ μm and Ag electrodes.