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Design of large-mode-area single-mode optical fiber with lowing bending loss for Raman distributed temperature sensor

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ABSTRACT

Numerical investigation on the design of a large-mode-area (LMA) single-mode photonic crystal fiber (PCF) as the sensing fiber for Raman distributed temperature sensor (DTS) is presented. The PCF can enable single-mode operation and have an extremely LMA exceeding 288 μm^2 when kept straight and over 284 μm^2 with a lower bending loss of 0.25 dB/m when bent over a 5 cm radius at a wavelength of 1550 nm. We outline the principles of our fiber design and explore the unique properties of the fiber for Raman DTS. Calculation results show that the Raman DTS system, which used the proposed PCF as the sensing fiber, can improve SNR about 3.4 times by increasing the input power compared with the Raman DTS system with a conventional single-mode fiber, because of the improved LMA, single-mode operation and good bending characteristics of the PCF.

1. Introduction

Optical fiber sensors have attracted much attention for a number of years as a new type of sensor owing to their simple structure, small volume, immunity to electromagnetic interference and remote sensing capability. Some of them have unique advantages in contrast to traditional sensors, especially for the real-time measurement of temperature field, strain field and pressure field in the space. The Raman distributed temperature sensor (DTS) based on spontaneous Raman scattering (SRS) is one of the high-tech equipments for real-time measuring the spatial distribution of temperature, which has been mostly used and investigated in recent years [1].

The Raman DTS usually uses an optical time domain reflectometry (OTDR) technique to monitor the temperature-dependent backscattered light along a conventional single-mode optical fiber in the majority of the previous report [2–4]. When a short pulse light is launched into one end of the sensing fiber, light is scattered within the fiber, which is classified as Raman scattering, Brillouin scattering and Rayleigh scattering. The ratio between the backward anti-Stokes Raman light intensity and Stokes Raman light intensity is used for temperature measurement. However, the intensity of backward SRS light is too weak to detect and susceptible to noise interference in the system, which limits the Raman DTS to further increase the measurement range and the temperature resolution. With the use of high peak power OTDR pulses for the excitation of SRS in the fiber, the intensity of backward SRS light can be further increased. However, the other detrimental nonlinear propagation effects, such as stimulated Raman scattering, will be excited simultaneously, which is bad for the Raman DTS.

Using a multi-mode fiber as the sensing fiber, it can allow a higher input peak power level before the threshold of the stimulated Raman scattering effect, and make the detected SRS signal to maximize [5], because the core diameter of the multi-mode fiber is larger than that of the SMF. However, it limits the best spatial resolution of several meters and the measurement distance below 10 km due to the modal dispersion. In order to avoid that problem, a LMA optical fiber with single-mode operation [6,7] is a good candidate as a sensing fiber for further improving the performance of Raman DTS effectively. However, most of the current commercial LMA fibers, such as the LMA-TDF-25/250 produced by Nufern Company, are few-mode fibers, which are not suitable for Raman DTS systems due to modal dispersion. On the one hand, the realization of a single-mode LMA in a conventional optical fiber is difficult, and the bending performance is another challenge for a LMA fiber.

A solution to this problem can be found by exploiting the unique wave guiding properties of photonic crystal fiber (PCF) [8], that allows single-mode operation with LMA in the fiber easily due to their flexible designing and special structures. Generally, such a PCF [9] can be defined as a single-mode fiber when the confinement loss of its higher-order modes (HOMs) is orders of magnitude larger than that of the fundamental mode (FM). Various LMA single-mode PCFs have been reported [10–12]. However, most

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of the demonstrated structures are asymmetric to avoid large bending loss in the fibers. Still these interesting and inspiring proposals have rather limited potential for practical Raman DTS applications. A few LMA single-mode bending-insensitive PCF with symmetrical structure have nevertheless been suggested.

In this paper, we propose a new structure of a LMA single-mode PCF with lowing bending loss for Raman DTS. Numerical results show that the designed LMA-PCF (D-LMA-PCF) that has a silica core surrounded by several rings of air holes with different diameters, can keep single-mode operation with mode area lager than 288 μm^2, and have negligible bending loss of 0.25 dB/m at the bending radius of 5 cm. In addition the proposed structure of the optical fiber can effectively prevent the bend-induced MFA reduction. This fiber with the improved LMA, single-mode operation and good bending characteristics will be potentially used for Raman DTS to obtain high signal-to-noise ratio (SNR) and high temperature resolutions by increasing the light input power largely. Calculation results show that the Raman DTS system, which used the proposed PCF as the sensing fiber, can improve SNR about 3.4 times compared with that of the Raman DTS system with a conventional single-mode fiber. We outline the principles of our fiber design and explore the unique properties of the fiber for Raman DTS.

2. Description of the designed PCF

Fig. 1 shows the cross-section of the D-LMA-PCF. The cladding of the fiber is composed of two types of air-holes with different diameter. d_1 stands for the diameter of smaller air holes, d_2 is the diameter of larger air holes, and Λ is the distance between adjacent air holes. The core is formed by the omission of one air hole in the center. A full-vector finite-element method (FEM) is employed to analyze the mode field distribution of the D-LMA-PCF. With an anisotropic perfectly matched layer (PML) instead of the absorbing conditions, the complex model effective index as well as the confinement loss can be calculated [17,18]. The silica refractive index is calculated by the Sellmeier equation as well as the air refractive index is considered as $n = 1$. Fig. 2 shows the mode field distribution of the FM for the fiber with $d_1 = 4$ μm, $\Lambda = 16$ μm, and $d_2/d_1 = 2.0$, where the operating wavelength is 1550 nm. We can see that the mode field distribution is the Gaussian distribution, and the mode area is 288 μm^2. Apparently, the D-LMA-PCF will have large-mode-area, owing to the large diameter of the core.

For the D-LMA-PCF, it can maintain an endlessly single-mode operation as long as we set the diameters of all air holes in the cladding is 4 μm and the pitch $\Lambda = 16$ μm, because the ratio between the air-hole diameter and the pitch is lower than the upper limit value of 0.424 for a conventional endlessly single-mode PCF with the core of which realized by the omission of one air hole in the center [13]. However, it will have large bending loss because of the lower refractive index difference between the core and the cladding. Therefore, to achieve both effectively single-mode operation and low bending loss in an LMA-PCF, we deliberately introduce two air hole rings with large diameters around the core. The large air holes will lead to high index difference between the core and the micro-structured cladding and, will be able to provide strong confinement to keep low loss when the fiber is bent.

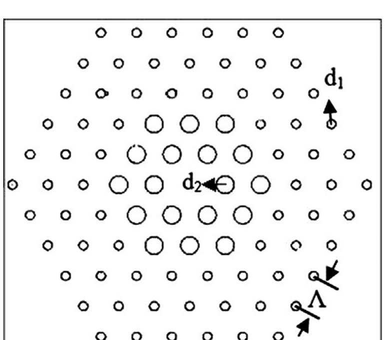

Fig. 1. The schematic cross section of the D-LMA-PCF. The air-hole diameter of the inner rings is d_2, and the rest air-hole diameter of the outer rings is d_1.

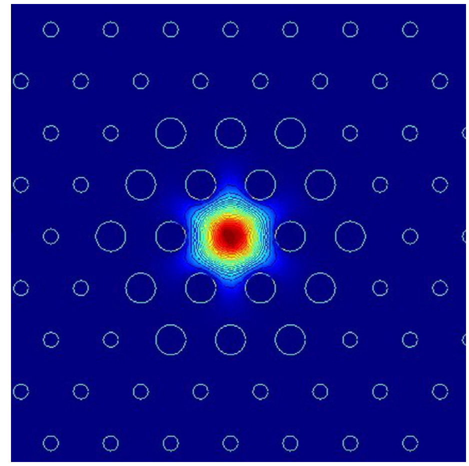

Fig. 2. The mode field distribution of the FM for the fiber with $d_1 = 4$ μm, $\Lambda = 16$ μm, and $d_2/d_1 = 2.0$, where the operating wavelength is 1550 nm.

According to the conformal transformation method [14], the equivalent refractive index of a bent fiber can be given in the x plane as follows:

$$n_{eq}(x,y) = n(x,y)\left(1 + \frac{x}{R_{bend}}\right) \quad (1)$$

where x is the distance from the center of the fiber cross section to the position along the bending direction, and $n(x,y)$ is the original refractive index profile of the straight fiber. We can see from the formula that the bending will lead to the increase of the equivalent refractive index both for the core and the cladding at $+x$-direction and, simultaneously, the reduction of the refractive index at $-x$-direction. Therefore, the FM mode of the optical fiber will shift toward outside due to bending, and the leakage of mode field will happen in the $+x$-direction when the bending radius is so small that the mode cannot be confined in the core. The bending loss can be expressed as follows [15]:

$$L_b = \frac{2 \times \pi \times 8.686 \times I_m(n_{eff})}{\lambda} \quad (2)$$

where n_{eff} is the wavelength dependent effective refractive index calculated by using the FEM method, $I_m(n_{eff})$ is the coefficient of the imaginary part of n_{eff}, and λ is the operate wavelength, respectively. Based on the simulation of the effective refractive index of the FM, we can also get the fiber's mode field area (MFA) [16]:

$$A_{eff} = \frac{\left(\int\int_S |E_t|^2 \, dxdy\right)^2}{\int\int_S |E_t|^4 \, dxdy} \quad (3)$$

where E_t denotes the electric fields vectors and S is the whole cross section of the PCF.

3. The properties of the D-LMA-PCF

In this paper, we define a PCF with a low confinement loss of the FM (less than 0.03 dB/m) and a high confinement loss of the HOMs