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Intensity detection scheme of sensors based on the modal interference effect of few mode fiber

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ABSTRACT

The transmission spectrum and power of the few mode fiber (FMF) under different strain/temperature are studied theoretically and experimentally. Significant shift of the critical wavelength of FMF can be produced when the measurement range is large. An intensity detection scheme with broadband source is proposed to overcome the problem encountered by the traditional measurement methods such as peaks shifts detection and transmission detection at a fixed single wavelength. And the scheme show larger dynamic range and larger linear operating range when the length of FMF is shorter, which can make the sensor more compact. The experimental result agrees well with the theoretical calculation.

1. Introduction

Intermodal interferometric sensors based on few mode or multimode fibers have been widely investigated for strain, temperature, curvature and refractive index measurements [1–4]. Since all the interference modes propagate in the same fiber, this sort of sensors can get rid of the problem of shielding reference arm, comparing with the traditional fiber interferometers such as the Mach–Zehnder or Michelson interferometers [5]. The modal interference based on the fundamental core mode, LP_{01}, and the first circularly symmetric high order core mode, LP_{02}, have been attracted special attentions, because they are polarization independent [6].

The modal interference between LP_{01} and LP_{02} modes results in periodical fringes in the transmission spectrum of FMF, and the transmission spectrum changes with strain, temperature and pressure variations. Various strain, temperature or pressure sensors can be constructed by monitoring the shifts of the peak wavelengthes and the intensity variation of fixed wavelength [7–11]. In some specific cases, a critical wavelength, λ_c, may appear in the transmission spectrum and several interesting characteristics can be observed as follows [12–16]: (1) the closer the wavelength to λ_c, the bigger the spacing between the adjacent peaks of the transmission spectrum; (2) the moving directions of the wavelength are opposite on the both sides of λ_c when the temperature or strain change; (3) the sensitivity increases greatly as the wavelength close to λ_c either from left or right side. Since the traditional intensity detection method utilizing narrow linewidth source at fixed wavelength will be invalid when the critical wavelength shifts as the measurement range of temperature or strain is sufficiently large, we propose an alternative intensity detection scheme using broadband source instead. The bandwidth of the broadband source is selected to be large enough to cover the largest wavelength spacing near λ_c and the shift of λ_c, so, the phase change of the interferometer results in the transmission power change within the bandwidth of the source. The novel detection scheme is capable of overcoming the problem of critical wavelength shift, and the length of FMF used in this scheme could be designed as short as several centimeters which makes the sensor more compact.

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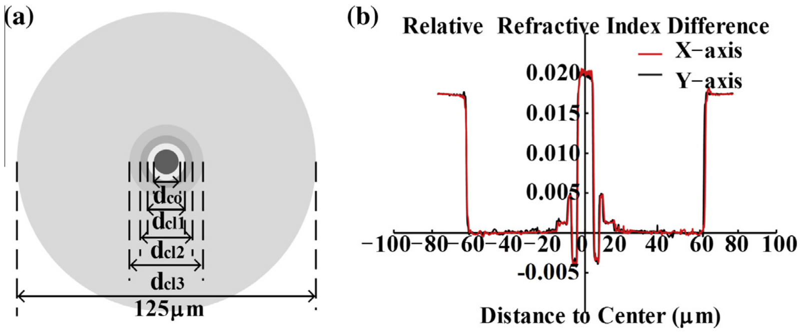

Fig. 1. Parameters of FMF. (a) The schematic cross section of the FMF; (b) the measured relative refractive index difference profile of the FMF at 670 nm. (d_{co}, d_{cl1}, d_{cl2} and d_{cl3} are the diameter of the core, first inner cladding, second inner cladding, and third inner cladding, respectively. The fiber parameters are: $d_{co} = 8$ μm, $\Delta n_{co} = 1.99\%$, $d_{cl1} = 14.3$ μm, $\Delta n_{cl1} = -0.40\%$, $d_{cl2} = 18$ μm, $\Delta n_{cl2} = 0.48\%$, $d_{cl3} = 30$ μm, $\Delta n_{cl3} = 0.14\%$).

2. Theoretical analysis

The FMF is specially designed with an inner core, three inner claddings, and a pure SiO_2 outer cladding so as to support only two modes: the fundamental mode, LP_{01}, and the first circularly symmetric higher order core mode, LP_{02}. The schematic cross section and relative index difference profile of the FMF measured at 670 nm are shown in Fig. 1(a) and (b), respectively. The relative refractive index difference is defined as $\Delta n_{co/cli} = (n_{co/cli} - n_0)/n_0$, where $n_{co/cli}$ and n_0 are the refractive indices of core/i th inner cladding of FMF and pure silica, respectively.

A piece of FMF was spliced between two SMFs to form the single mode fiber (SMF)–few mode fiber (FMF)–single mode fiber (SFS) structure, depicted in Fig. 2.

LP_{01} and LP_{02} mode in FMF are excited by the fundamental mode LP_{01} of the input SMF at the first joint. The intermodal interference between LP_{01} and LP_{02} mode is selected by the output SMF, the transmission through the FMF is written as [15]:

$$T = P_{out}/P_{in} = t_{01}^2 + t_{02}^2 + 2t_{01}t_{02}\cos(\varphi(\lambda)) \quad (1)$$

where t_{01} and t_{02} are the power transferred ratios of the fundamental mode LP_{01} of the input SMF to the LP_{01} and LP_{02} modes of the FMF. Noted that $t_{01} : t_{02}$ determines the contrast of the interference fringes [6]. When $t_{01} : t_{02} = 1$, the contrast of the interference fringes can reach the maximum. Here, t_{01} and t_{02} are calculated to be 80% and 19% utilizing the parameters given in Fig. 1 (a) and (b) and APSS (Apollo Photonic Solutions Suite, APOLLO PHOTONICS in Canada), when the input SMF is perfectly aligned with the FMF. $\varphi(\lambda)$ is the phase difference between LP_{01} and LP_{02} modes, which is given as:

$$\varphi(\lambda) = \Delta\beta(\lambda)L \quad (2)$$

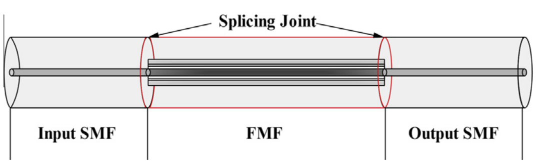

Fig. 2. Diagram of SMF–FMF–SMF (SFS) structure.

where L is the physical length of the FMF. $\Delta\beta$ is the propagation constant difference between the LP_{01} and LP_{02} modes.

The phase difference is a function of both the operating wavelength λ and the perturbation parameter (temperature or strain). Therefore [12]:

$$\Delta\varphi = \frac{\partial\varphi}{\partial\lambda}\Delta\lambda + \frac{\partial\varphi}{\partial\chi}\Delta\chi \quad (3)$$

For constant phase points we have the wavelength sensitivity with perturbation parameter:

$$\frac{\Delta\lambda}{\Delta\chi} = -\frac{1}{L}\left(\frac{\partial\varphi}{\partial\chi}\right)\left(\frac{\partial(\Delta\beta)}{\partial\lambda}\right)^{-1} \quad (4)$$

where $\partial\varphi/\partial\chi$ can be calculated according to [9]. $\Delta\lambda/\Delta\chi$ is in inverse proportion to $\partial(\Delta\beta)/\partial\lambda$. $\Delta\beta$ is calculated by APSS, shown as dashed line in Fig. 3. The simulated results show that $\Delta\beta$ does not show monotonic behavior with wavelength, and reaches maximum at a special wavelength. The corresponding transmission spectrum is calculated by Eq. (1) with simulated $\Delta\beta$, depicted as the solid line in Fig. 3. It has periodic peaks with a critical wavelength (@ 1557.91 nm, coinciding excellently with the measured value 1557.89 nm), where corresponding $\Delta\beta$ reaches maximum. The spacing between the adjacent peaks at critical wavelength is much broader than others and the transmittance varies with temperature and strain. When the critical wavelength shifts, the sensitivity of peaks change significantly, especially for the peaks near the critical wavelength. Neither peaks shift detection method nor traditional intensity detection method utilizing narrow linewidth source at fixed wavelength are invalid.

The measured critical wavelength shows 2.46 nm red shift (from 1557.89 nm to 1560.35 nm) when the temperature changes from 24 °C to 80 °C, seen in Fig. 4.

Considering the spectrum character, the intensity of Amplified Spontaneous Emission (ASE) broadband light source changes after it transmits through the broadband filter formed by the SFS structure. The normalized output power ($P_{out}/P_{max\text{-}out}$) of intensity after transmit through the normal SFS filter without critical wavelength, filter 1, and the SFS filter with critical wavelength, filter 2, under different strain is compared in Fig. 5(c). The spectrum of