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Investigation on a compact in-line multimode-single-mode-multimode fiber structure

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We carried out a detailed investigation on a compact in-line multimode single-mode multimode (MSM) fiber structure. Both theoretical modal and experimental setup were established to demonstrate the transmission characteristics and the corresponding responses of the applied strain and temperature. The proposed structure simply involves a section of the single-mode fiber (SMF) spliced to two sections of multimode fiber (MMF) and lead-in and lead-out SMFs. The excited environment-sensitive cladding modes together with the fundamental mode in the central SMF form a typical Mach–Zehnder interferometer (MZI). We analyzed the transmission characteristics of the different length of the middle SMF and the MMF in detail. In the experiment, we obtained the extinction ratio of the MSM fiber structure based MZI comb spectrum which was up to 20 dB, and sensitivities of 0.7096 pm/με (0–2000 με) and 44.12 pm/°C (10–70 °C), which proved the potential sensing applications of the proposed fiber structure.

1. Introduction

The multimode interference (MMI) theory in the planar waveguide has been extensively investigated and proposed as a basis for a number of novel fiber devices such as beam splitters, combiners, multiplexers for optical communications, comb filters and fiber sensors [1–5]. Recently, the MMI occurring in the single-mode-multimode-single-mode (SMS) fiber structure has been investigated and proposed as all-fiber solutions for optical communications, bandpass filter and optical sensing with the advantages of simple structure, low cost, high stability, and ease of packaging and connection to optical system. The devices of the SMS fiber structure have been extensively used for various sensor applications, such as the displacement sensor, the strain and temperature sensor, the refractometer sensor, and the curve sensor [6–12]. The typical all-fiber structure based on the modal interference can be also fabricated by fusion splicing a short section of the single mode fiber (SMF) between two sections of the multimode fiber (MMF), and the MMI occurring in the multimode-single-mode-multimode (MSM) fiber structure also has the same advantages as the SMS fiber structure. Different from the SMS fiber configuration, the MSM fiber structure [13,14] utilizes the interference between the core mode and the cladding modes propagated in the SMF. Comparing with SMS fiber structure, the MSM fiber structure is more compact with the same free spectrum range (FSR) and potentially provides more homogeneous property. And because of the large effective index difference between the cladding mode and the core mode, it is possible to enhance the sensitivity in surrounding sensing applications like refractive index, solution concentration or liquid level [15,16]. Linh et al. presented the MSM fiber structure based Mach–Zehnder interferometer (MZI) sensor for high temperature measurement [13]. Wu et al. presented the fiber sensor based on MSM fiber structure and FBG for measuring the strain and temperature simultaneously [17]. Tang et al. proposed the magnetic-fluid-clad MSM fiber structure for the magnetic field sensing sensitivities of 215 pm/mT and 0.5742 dB/mT which was obtained for interference dip around 1595 nm [18]. Zhang et al. presented a theoretical and experimental investigation on refractive index (RI) sensing characteristics of MSM fiber structure based modal interferometers [16]. However, a detailed analysis of the MSM fiber structure in terms of the parameters of the structure and the outside environment has still not been done.

In this paper, we theoretically investigate the variation of the mode excitation coefficient in middle SMF which is spliced to different length of MMF. The result shows that the power distribution in the middle SMF is highly dependent on the length of MMF1. The MSM structure can obtain a homogeneous interference fringe since the power in middle SMF will concentrate in fewer modes by a specific length section of MMF. The MZI is fabricated by cascaded fusion splicing two similar SMS fiber structure with

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similar transmission spectrum. In the meanwhile, the relationship between the transmission spectrum and length of SMF is also experimental investigated. Additionally, we proposed an effective fiber cleave approach for splicing a special section of MMF to SMF accurately. The characters of the MSM fiber structure exhibits the axial strain and temperature sensitivity of 0.7096 pm/με (0–2000 με) and 44.12 pm/°C (10–70 °C), respectively.

2. Principle

2.1. Mode coupling in the MSM fiber structure

The configuration of the MSM fiber structure is shown in Fig. 1. The structure is fabricated by fusion splicing one segment of SMF between two short sections of the MMF. The basic principle of the MSM fiber structure is based on the modal interference between the core mode and the cladding modes propagated in the uncoated SMF [19]. The two sections of MMF separately act as the mode splitter and combiner. Due to the uniform refractive index distribution and large core diameter, step index MMF can excite plenty of cladding modes into SMF by the mode field mismatch. More importantly, the power distribution of the cladding mode in uncoated SMF can be changed by varied length of MMF.

When an input field from the lead-in SMF directly couple into MMF1, it is necessary to determine which modes are excited in the MMF section. Assume that the fusion splice between lead-in SMF and MMF are axially aligned and both the lead-in SMF and MMF have circular cross section, and the input field from lead-in SMF is $\varphi_s(r)$. The field distribution can be written as a series expansion of guided mode in the MMF.

$$\varphi_s(r) = \sum_{n=1}^{N} c_n \varphi_n(r) \tag{1}$$

where $\varphi_n(r)$ is the field distribution of the nth order mode supported in the MMF core. It is known that the excited coefficient determines the power ratio of each specific mode in MMF. And the coupling coefficient of the power can be determined using the following equation

$$c_n = \frac{\int_0^\infty \varphi_s(r)\varphi_n(r) r dr}{\int_0^\infty \varphi_n(r)\varphi_n(r) r dr} \tag{2}$$

After propagated a distance of z, the total field φ in MMF core section can be expressed as

$$\varphi(r, z) = \sum_{n=1}^{N} c_n \varphi_n e^{-j\beta_n z} \tag{3}$$

The β_n is the propagation constant of the nth mode in MMF. At the fusion splice point between the MMF1 and uncoated SMF, part of the power of nth mode couples into the uncoated SMF core and the other part couples to cladding modes of the uncoated SMF.

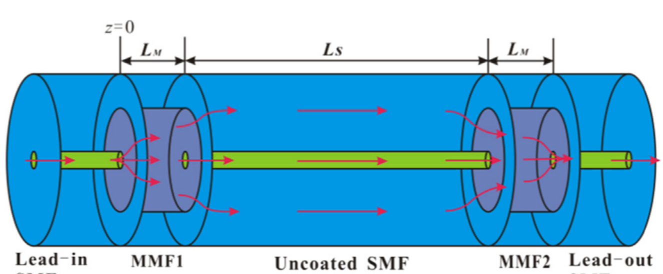

Fig. 1. Schematic of the MSM fiber structure.

Similarly to Eq. (2), the coupling coefficient of the mth cladding mode in uncoated SMF can be written as

$$d_m = \frac{\int_0^\infty \left[\sum_{n=1}^{N} c_n \varphi_n(r, L_M)\right] \psi_m(r) r dr}{\int_0^\infty \psi_m(r)\psi_m(r) r dr} \tag{4}$$

where L_M is the length of MMF, $\Psi_m(r)$ is the field distribution of order mode in uncoated SMF. Eq. (4) indicates that the excitation of the mth mode in uncoated SMF is dependent on the phase of the nth order mode guided in MMF. In the other words, the field distribution in uncoated SMF and the transmission spectrum of the MSM fiber structure are influenced by the length of the MMF1.

Assuming that the MZI cavity is L_s, the field of the uncoated SMF section can be calculated by

$$\psi(r, L_s) = \sum_{m=1}^{M} d_m \psi_m e^{-j\beta_m L_s} \tag{5}$$

Similarly, at the fusion splice point between uncoated SMF and MMF2, part of the cladding mode of the uncoated SMF couples to the guided modes in MMF. Thus, the modal interference occurs between the fundamental core mode and the higher order cladding modes of the uncoated SMF in sections of MMF2.

At the interface of the MMF2 and lead-out SMF, partly core modes in MMF couples back to the fundamental modes in lead-out SMF. And the transmission loss can be approximately as

$$\text{Loss} = 10 \log_{10} \frac{\left|\int_0^\infty \varphi_{out}(r)\varphi_s(r) r dr\right|^2}{\int_0^\infty |\varphi_{out}(r)|^2 r dr \int_0^\infty |\varphi_s(r)|^2 r dr} \tag{6}$$

In order to investigate the transmission spectrum of the MSM fiber structure based MZI, we calculate the power distribution in uncoated SMF and the transmission spectrum of the MZI with MMF lengths of 1.2, 1.4 and 1.6 mm. The length of uncoated SMF is 8 cm in the calculation. The core/cladding diameter of the SMF and MMF used in the calculation is 8.06/125 μm and 50/125 μm. The numerical aperture of the MMF is 0.22. We assume that the core refractive index (1.4446) of the MMF is same to the cladding refractive index (1.4446) of the SMF, and the core refractive index of the SMF is 1.4505. The power distribution with different length of MMF in the core and cladding sections of SMF is calculated by Eqs. (1)–(4), and the simulated results are shown in Fig. 2(a).

When the length of MMF is 1.2 mm and 1.4 mm as shown in Fig. 2(a), there are little variations of the mode coupling coefficients with the wavelength ranging from 1500 nm to 1600 nm. However, the power distribution in the SMF is scattered in multiple cladding modes with MMF length of 1.2 mm, which makes the interference fringe inhomogeneous. When the length of the MMF comes to 1.6 mm, the mode coupling coefficients are dependent on the wavelength seen clearly in Fig. 2(a). The appearance can be seen clearly in the spatial frequency spectrum (corresponding to Fig. 2(b)) shown in Fig. 2(c). From the spatial frequency spectrum, it is clear that the 1.6 mm length of the MMF has more frequency components than the 1.4 mm length of the MMF.

We also observe that the coupling coefficient of LP_{02} and LP_{03} cladding modes is larger than 0.1, and the intensity ratio of the first three modes is ~90% with MMF length of 1.4 mm. It is known that the free spectrum range between any two interference modes is dependent on the length of uncoated SMF in this structure (see the interpretation in the following section). Thus, it can be inferred that the interference between LP_{02} and LP_{03} can strongly modulate the interference pattern of the MSM fiber structure based MZI when the SMF cavity is long enough. Therefore, the SMF length should be controlled to avoid the interference fringe between LP_{02} and LP_{03} mode which falls into the measured wavelength band