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# Fabrication and sensing characterization of thermally induced long period fiber gratings in few mode fibers

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ABSTRACT

In this work, the long period fiber gratings (LPFGs) in few mode fibers are investigated systematically. A simple but effective method is employed to fabricate the thermally induced LPFG with asymmetric structure. When few mode fibers with LPFG are spliced between two single mode fibers, the obvious dip can be observed in the transmission spectrum. The mechanism of the transmission dip can be explained by the mode conversion process from $LP_{01}$ to $LP_{11}$, which is identified by both theoretical analysis and the mode field measurements in FMF. The resonance wavelength of FMF-based LPFG is sensitive to applied strain and temperature. The sensitivities of strain and temperature measurements are 5.4 pm/$\mu\varepsilon$ and 58.9 pm°C respectively. Because cladding modes are not involved in the mode conversion process, the LPFGs fabricated in this method are not sensitive to the environmental refractive index. It is suitable for the measurements of temperature and strain in the environment with variable refractive index.



## 1. Introduction

In the last two decades, few mode fibers (FMFs) have been intensively studied due to their potential to overcome the capacity limit of the optical communication based on standard single mode fibers (SMFs) [1,2]. Because the FMFs support a small number of modes in core layer, they provide more capacities and flexibilities than SMFs in optical communication by utilizing the space division multiplexing technology. Moreover, FMFs can also be employed to develop fiber optical sensors [3–7]. By exploring the unique properties of high order modes of FMFs, the optical fiber sensors can be developed with high sensing performance [4]. For this purpose, how to excite high order mode in FMFs becomes an important issue. The core offset splice between standard SMFs and FMFs is employed in order to generate the high order modes of FMFs under the incidence from SMFs [8]. However, the generation efficiency for each mode is difficult to control. In most cases, some modes in FMFs are excited by the offset splice structure simultaneously. The selective excitation of a specific high order mode in FMFs can be achieved by using planar phase plates [4]. In this technology, the alignment of the optical devices is difficult in free space optical system. Compared with this method, long period fiber gratings (LPFGs) are more compact and flexible in practical applications due to their all-fiber structures [9–11]. The mode conversion between two fiber modes can be achieved with high efficiency when the resonance condition is fulfilled. In fact, the LPFGs on FMFs can be fabricated by some different kinds of technologies, including acoustic wave [12], mechanical micro-bending [13] and $CO_2$ laser pulse [14]. However, in most of these works, the sensing properties of these grating structures have not been fully explored. According

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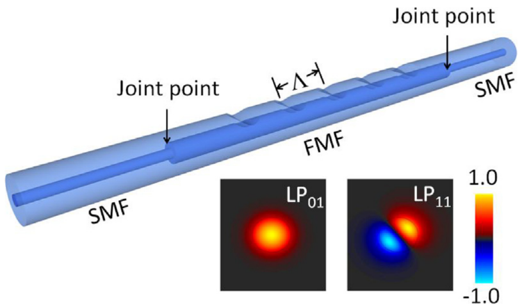


**Fig. 1.** The schematic of the LPFG written in FMF segment of the SMF-FMF-SMF structure. The insets show the electric field distribution of $LP_{01}$ and $LP_{11}$ modes in FMF.

to the previous work [7], the resonance wavelength of the LPFG on FMF is sensitive to strain and temperature applied on four-mode FMFs. When the four-mode FMF is inserted between two single mode fibers, the mode interference between $LP_{01}$ and $LP_{02}$ modes in the FMF may influence sensing results of the LPFG in FMF.

In order to solve this problem, two-mode fiber has been employed in this work. The LPFGs in few mode fibers are fabricated to realize the mode conversion between $LP_{01}$ and $LP_{11}$ mode by a low-cost heating method. When the FMF segment with LPFGs is inserted between two SMFs, the formed structure can be developed for strain and temperature measurements. The sensing performance of the structure is characterized numerically and experimentally. Compared with the LPFGs in SMF, the FMF-based LPFGs proposed in this work are insensitive to the environmental refractive index, because only the core modes are involved in the mode conversion process. FMF-based LPFG is suitable for the measurement of temperature or strain in the environment with variable refractive index.

## 2. Theoretical analysis

The designed structure of the FMF-based LPFG is shown in Fig. 1 . A segment of FMF with LPFG is spliced between two SMFs (SMF-28e, Corning). The FMF employed in this work is a step-index two mode fiber, which only supports the $LP_{01}$ and $LP_{11}$ modes. The SMF and FMF are well aligned without any core-offset during the splicing processes. The incident light is from the input SMF. Due to the restriction by mode orthogonal characteristic, the $LP_{01}$ mode in the input SMF cannot couple with the $LP_{11}$ mode in FMF, and only the $LP_{01}$ mode in FMF is excited at the first joint. At the resonance wavelength of the LPFG, the $LP_{01}$ mode can be converted to $LP_{11}$ mode. At the second joint between FMF and the output SMF, the excited $LP_{11}$ mode cannot couple into output SMF fiber in the form of $LP_{01}$ mode. In this case, the transmission loss of the proposed structure can be caused by the mode conversion process.

The power loss of the transmitted light is related to the conversion process of LPFG. According to the coupled mode theory, the z-dependent mode amplitudes for $LP_{01}$ ($A_{01}$) and $LP_{11}$ ($A_{11}$) in LPFGs should fulfill the differential equations as follows:

$$\frac{dA_{01}}{dz} = j\kappa_{01-01}A_{01} + \frac{j}{2}\kappa_{01-11}A_{11}e^{-j\delta z}, \tag{1a}$$

$$\frac{dA_{11}}{dz} = j\kappa_{11-11}A_{11} + \frac{j}{2}\kappa_{11-01}A_{01}e^{j\delta z}, \tag{1b}$$

where $\delta$ is the detuning parameter, defined as $\delta = \beta_{01}$-$\beta_{11}$-$2\pi/\Lambda$. $\beta_{01}$ and $\beta_{11}$ are the propagation constants of $LP_{01}$ and $LP_{11}$ modes in FMF. $\Lambda$ represents the grating period. The coupling coefficient $\kappa_{\mu\text{-}\nu}$ between mode $\mu$ and mode $\nu$ can be calculated by Eq. (2).

$$\kappa_{\mu-\nu} = \frac{\pi}{\lambda}\iint_{S_1}\Delta\varepsilon(r,\theta)\mathbf{E}_{\mu}(r,\theta)\cdot\mathbf{E}_{\nu}(r,\theta)ds, \tag{2}$$

In Eq. (2), $\Delta\varepsilon(r, \theta)$ represents the perturbation of the grating region. $\mathbf{E}_{\mu}(r,\theta)$ and $\mathbf{E}_{\nu}(r,\theta)$ are the field distributions of fiber modes. The mode conversion efficiency can be expressed as the ratio between the converted mode ($LP_{11}$) power and incident mode ($LP_{01}$) power. For a LPFG with length $L$, the conversion efficiency can be calculated by $|A_{11}(z=L)|^2/|A_{01}(z=0)|^2$. The insets of Fig. 1 show the field distributions of these two modes when $\lambda = 1550$ nm. By calculating the integral in Eq. (2), one can prove that coupling coefficient $\kappa$ is zero if the grating perturbation is independent with the azimuthal angle $\theta$ (i.e. circular symmetry). In this work, the asymmetric LPFGs, like the periodical multi-notch structure as shown in Fig. 1, is designed and fabricated to realize the mode conversion between core modes in FMFs.

In order to determine the resonance condition of LPFG, mode analysis should be carried out for the FMF fiber. In this work, the core diameter of the FMF is 15 μm. The refractive index of the core layer and the cladding layer is $n_1 = 1.465$ and $n_2 = 1.46$. By solving the eigen-equation of the FMF, the effective indices of $LP_{01}$ and $LP_{11}$ modes in the wavelength range of 1300 nm ∼ 1800 nm are shown by the black and blue curves in Fig. 2(a) respectively. It can be proved that the