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# Highly sensitive curvature sensor based on long period fiber grating with alternately splicing multiple single/multimode structure

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ABSTRACT

A highly sensitive curvature sensor made of a novel long period fiber grating (LPFG) is presented and experimentally demonstrated. It is constructed by splicing multiple single mode fibers (SMFs) and multi-mode fibers (MMFs) alternately (MS/MA). The measurement result shows that it has a high sensitivity of −22.4 nm/m$^{-1}$ in the range from 0.223 m$^{-1}$ to 4.358 m$^{-1}$. It can measure curvature on all direction due to the symmetric structure. The proposed sensor was also insensitive to the temperature, whose temperature sensitivity was around −0.015 nm/°C in the range from 40 °C to 200 °C. The advantages of high curvature sensitivity and low temperature sensitivity make it has a great potential to measure curvature in practical application with high resolutions.

## 1. Introduction

Long period fiber grating has attracted great research interest among the optic research community in recent years. Since it was first introduced by Vengsakar et al. in 1996 [1]. LPFGs have been widely used in detecting applications of many physical quantities, such as strain, temperature, refractive index and curvature due to its intrinsic advantages, including simple manufacture technology, low insertion loss, ultra-low reflection and high sensitivities of temperature, refractive index and torsion bend [2–5]. Moreover, Shijie Zheng and Yinian Zhu et al. proposed photonic crystal fiber based LPFG structure which can achieve the demand of detecting multiple gas species and humidity with high sensitivity or even monitoring structural health condition [6–9]. Optical fiber curvature sensor has attached great importance because of many applications in field of composite structure, like manipulator and machinery parts. LPFGs are more sensitive to curvature than Fiber Bragg Gratings (FBGs) and the resonant wavelength of LPFGs shift linearly with the curvature applied. In recent years diverse optical fiber curvature sensors were proposed, for example Ming Deng et al. fabricated an highly sensitive curvature sensor based on Mach-Zehnder interferometer (MZI) which were composed of photonic crystal fiber (PCF) (3.046 nm/m$^{-1}$) [10], Huaping Gong et al. fabricated a curvature sensor based on PCF interferometer (4.45 nm/m$^{-1}$) [11], and Kai Ni et al. created a curvature sensor based on taper PCF interferometer (8.35 nm/m$^{-1}$) [12] and Woojin Shin et al. presented a curvature sensor based on in-line fiber MZI in solid core large mode area PCF (3.05 nm/m$^{-1}$ from 0 to 0.9 m$^{-1}$; 36.16 nm/m$^{-1}$ from 0.9 to 1.2 m$^{-1}$) [13]. In addition, the bend-sensitivity of common LPFG and some other hybrid structure is dependent on the bend-direction, such as $CO_2$-laser-notched LPFG [14–16], core-offset SMF based sensor [17] *etc*. However, they can hardly measure curvature accurately unless on the determined bend-direction. To overcome the problem mentioned above, it is very necessary to fabricate a kind of curvature sensor which can not only measures curvature accurately on the all direction, but also has a high sensitivity.

In this paper, we presented a highly sensitive curvature sensor based on a novel LPFG which is constructed by splicing multiple SMF and MMF alternately. This fabrication method is more cost effective compared to the $CO_2$ laser irradiation technique which is using a focused $CO_2$ laser beam to irradiate a fiber periodically along its axis direction. The sensitive curvature sensor presented in this paper is shown to be able to achieve multimode interference. This LPFG can be applied to measure curvature by measuring its spectral change. It exhibits a high curvature sensitivity of −22.4 nm/m$^{-1}$ in the range from 0.223 m$^{-1}$ to 4.36 m$^{-1}$. Moreover, this curvature sensor has a high stability of the sensitivity because the curvature sensitivity will not change with the bend-direction.

## 2. Fabrication and principle

The novel multiple SMF/MMF alternately splicing LPFG (MS/MA-LPFG) is fabricated through the cleaving-splicing method (CSM). The fabrication setup of this sensor consists of a fiber cleaving system and a fusion splicer, the diagram of it is shown in Fig. 1. With cleaving

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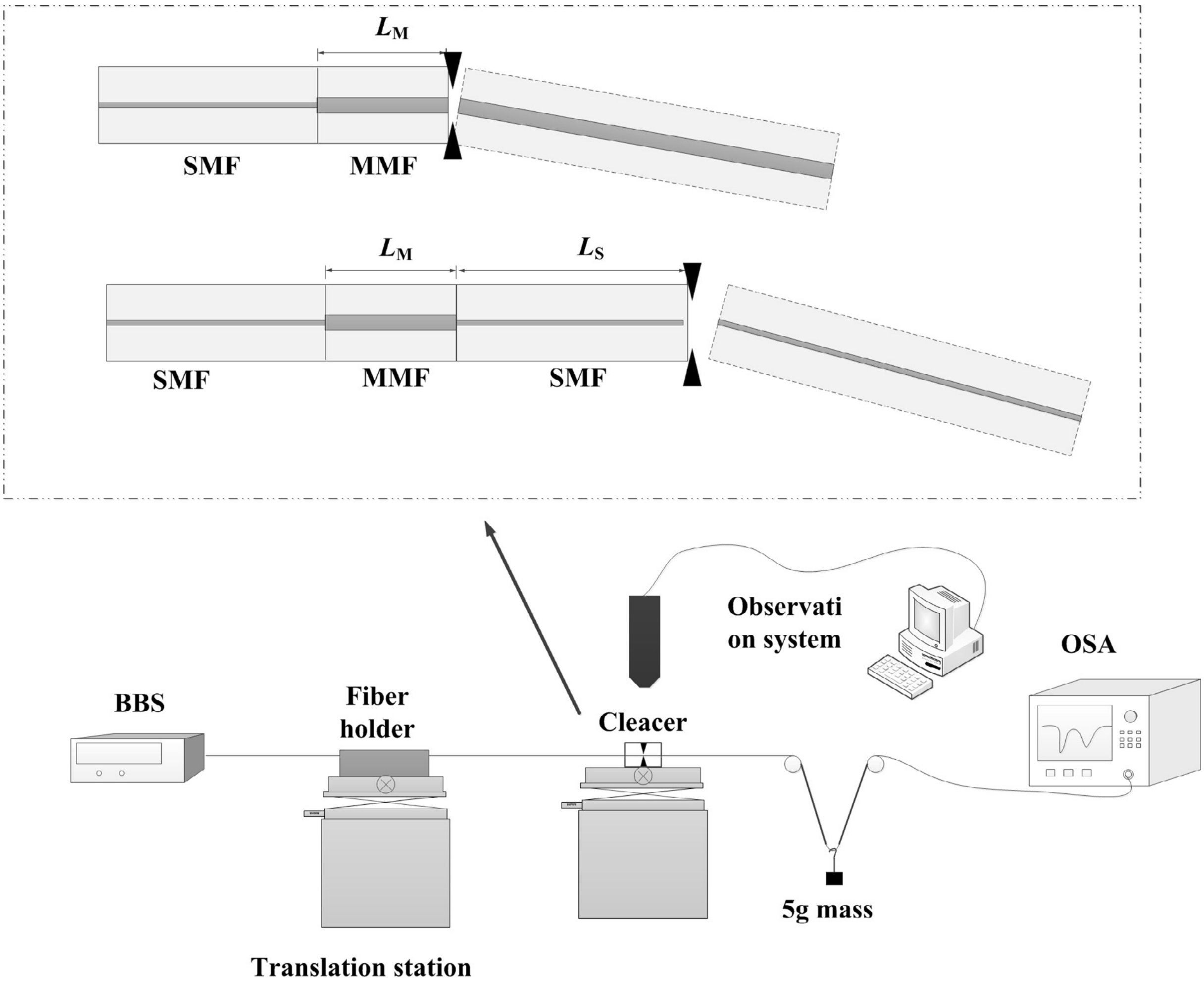


**Fig. 1.** Schematic diagram of the SMF/MMF alternately splicing LPFG.

system, optical fiber could be cleaved into desired length and each fiber's end face has a good quality. The setup includes four parts: two three-axis translation stages with a readable accuracy of 0.5 um, a high precision fiber cleaver (Proskit-FB-1688), an arc discharge fusion splicer (Nuotian NT-400), and a set of real-time observation and microphotograph device.

From Fig. 1, MMFs (62.5/125 um) and SMFs are fusion spliced alternately. Manufacturing process is decomposed into 3 main steps. Firstly, get a SMF and a MMF ready. Remove the middle part of coating and put the straightened SMF on the fiber holder which is fixed on the three-axis translation stage, a 5 g weight is suspended on the fiber. The bare section is placed in fiber cleaver. Secondly, cleave the fiber, then, put the left end of SMF in the fusion splicer and splice it with MMF without loosen the fiber holder during the whole procedure. Put the other end of fiber aside. Finally, move the three-axis translation stage where the cleaver is located by a desired length, and then cleave the MMF. Repeat these steps and use MMF and SMF interchangeably in step two. After all the splicing, an optical spectrum analyzer (OSA) is used to detect the transmission spectrum of this structure with a super-continuum source (SCS) serving as light source. $L_M$, $L_S$ and $\Lambda$ are introduced to denote the length of each MMF, SMF and grating period, respectively. The micrograph of this LPFG is illustrated in Fig. 2.

The sketch diagram of this sensor is presented in Fig. 3. Several MMFs (62.5/125 um) and SMFs are fusion spliced alternately. When the light emitted from SCS transmits from the lead-in SMF into the MMF, only the radial modes can be excited owing to the circular symmetric of SMF input filed as well as the field inside SMF [18]. According to the power coupling coefficient for all excited modes

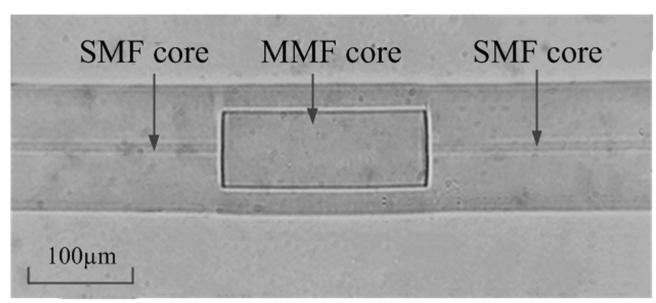


**Fig. 2.** The micrograph of a LPFG segment.

mentioned in Ref. [19], part modes are effectively excited inside the MMF core. At the first MMF-SMF interface, partial light from MMF enters the core of the SMF while the other part is coupled into the cladding due to the core diameter of MMF is several bigger than SMF. When a number of SMF/MMF splicing points are arranged periodically along the fiber axis with a pitch of hundreds micrometers, part of the high order modes will be periodically coupled from the radial mode, if the phase match condition is satisfied[20]. Then, the resonant peak can be observed from transmission spectrum, and the resonant peak position $\lambda_{res}$ can be calculated by using the phase match condition [21]. The effective refractive indices of cladding mode and core mode are presented by $n_{co}^{eff}$ and $n_{cl}^{eff}$, respectively.

$$\lambda_{res} = (n_{co}^{eff} - n_{cl}^{eff})\Lambda \quad (1)$$

The characteristics of this novel LPFG are affected by external