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# In-fiber Mach–Zehnder interferometer based on multi-mode fiber and up-taper for curvature sensing

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ABSTRACT

A new type of curvature sensor comprises a stub of multi-mode fiber and an up-taper is proposed and demonstrated experimentally. The whole fabrication process is quite simple and the sensor head is cost effective. Measurement results show that it has a maximum curvature sensitivity of $-61.877\ nm/m^{-1}$ at $1.1718\ m^{-1}$ (the highest value of reported papers among in-fiber Mach–Zehnder interferometers) and $-9.2115\ nm/m^{-1}$ from $0.865\ m^{-1}$ to $1.1172\ m^{-1}$. Temperature sensitivity of 89.01 pm/°C within the range of 20–80 °C has also been achieved, which implies the possibility for measurement of temperature.


## 1. Introduction

In fiber Mach–Zehnder interferometers (MZI) have attracted great research interest for their compact structures, easy fabrication and low cost. An in Fiber MZI can be formed by introducing a mode-splitter and a mode-combiner to realize the coupling and re-coupling of core mode and cladding mode, which has been widely used for measurement of various parameters, such as refractive index, temperature, strain, etc. [1–3]. Most curvature sensors based on in-line MZIs are fabricated by splicing different kinds of fibers, for instance, a multimode fiber (MMF) between two sections of single mode fibers (SMF) [4,5], or splicing two silica fibers into a photonic crystal fiber (PCF) [6,7], or a polarization maintaining fiber (PMF) [8]. However, The curvature sensitivity of those structures based on PCF or PMF is low. Frazão proposed a Mach–Zehnder interferometer exploiting multimode fiber cascaded with long-period grating [9]. A MMF with a fiber Bragg grating (FBG) [10] was also proposed. These configurations based on FBG or LPG require expensive ultraviolet light laser source, phase mask and sophisticated fabrication technology.

In this paper, we propose a new type of curvature sensor composed of a section of MMF and a up-taper. The fabrication process of our sensor is quite simple and cost effective. The proposed curvature sensor exhibits a high sensitivity of $-61.877\ nm/m^{-1}$ at $1.1718\ m^{-1}$ and $-9.2115\ nm/m^{-1}$ from $0.865\ m^{-1}$ to $1.1172\ m^{-1}$. Which is much higher than the PCF based interferometer ($3.046\ nm/m^{-1}$ [5], $4.06\ nm/m^{-1}$ [6]), SMS based curvature sensor($8.7\ nm/m^{-1}$ [4]), also larger than the curvature sensor combining lateral offset with up-taper ($11.987\ nm/m^{-1}$ [11]) for range near $1.1718\ m^{-1}$.

## 2. Sensor fabrication and operation principle

The proposed structure is fabricated by introducing a section of multi-mode fiber (MMF) sandwiched between two single mode fiber (SMF) and an up-taper, as depicted in Fig. 1(a). Fig. 1(b) shows the image of the special splicing point. The MMF used in the experiment was fabricated by Yangtze Optical Fiber and Cable Company Ltd., which has a core and cladding diameters of 105 and 125 μm respectively.

Due to the core mismatch, light from the transmission fiber is partially coupled into the cladding of the middle SMF through the MMF. Part of SMF cladding mode is then re-coupled into the core at the following up-taper splicing point. Due to the phase difference between the cladding mode and the core mode of the middle SMF, a typical MZI is obtained. When the SMF is subjected to external bending, refractive index and optical path of cladding modes change, so the phase difference change, and dip wavelength shift accordingly, while the refractive index and profile of core mode can be considered constant. From the relationship of cladding mode's

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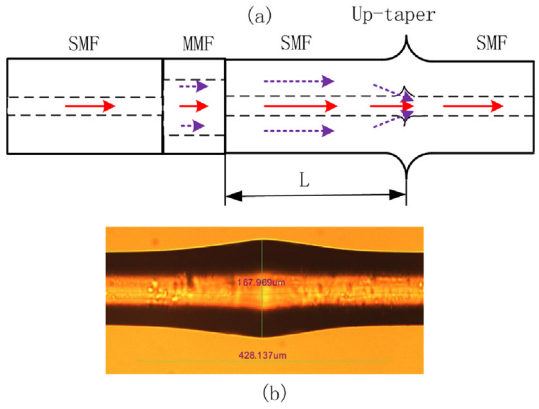


**Fig. 1.** (a) Structure of the curvature sensor comprise a section of MMF and an up-taper (b) splicing image of the Up-taper.

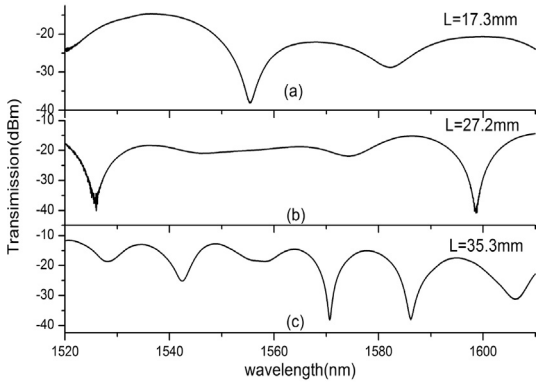


**Fig. 3.** Transmission spectra of MZIs with different interferometer lengths: (a) 17.3 mm, (b) 27.2 mm (c) 35.3 mm.

effective index with curvature reported by Block et al. [12], we can get that for some modes ($LP_{04}$, $LP_{12}$, $LP_{21}$), the effective indexes decrease with curvature, while it will increase for modes such as $LP_{02}$, $LP_{03}$, $LP_{13}$. So the orientation of wavelength shift is determined by which group of cladding modes participate dominantly in interfering with core modes. If the index of cladding modes involved in interference process increase as curvature increasing, a blue shift of dip will be seen.

The theoretical analysis of the SMS fiber structure has been reported in many literature [5,10]. So here we do not give extra introduction, the MMF is only exploited for exciting cladding modes, not for the interference between multiple guiding modes of MMF. In order to reduce the envelope modulation on the interference pattern and temperature impact, we choose the length of MMF as short as 1 mm. Multimode interference is theoretically supposed to be in the interference spectrum, but actually it cannot be seen in the transmission spectra for that interference between the multimode fiber Eigen-modes has very large free spectral range (FSR), and it does not fall into the measured wavelength range, as can be seen from the red curve in Fig. 2.

In order to form a waist-enlarged fiber taper, a large "overlap" of 150 μm is set through the conventional fiber splicer (FSM-60S), while other parameters (such as arc power, arc duration time, etc.) remain unchanged, just as the default values. From Fig. 1(b), the waist diameter and length of the up-taper are measured to be 168 μm and 428 μm, respectively.

To analyze the sensor operation, we record the spectrum of the broadband optical source, the transmission spectrum of the sensor with a stub of MMF (about 1 mm) alone, a up-taper alone and the transmission spectrum of the sensor combines a stub of MMF with an up taper, as shown in Fig. 2. Except for obvious source power decreasing, the transmission spectrum of MMF alone and up-taper alone is as same as that of the light source (no interference fringes observed). Only when the sensor comprises both MMF and up-taper, interference fringes appear, which is shown as the green curve in Fig. 2.

A batch of sensors were fabricated by splicing different lengths of SMF between MMF and the up-tapered region (e.g. 17.3 mm, 27.2 mm and 35.3 mm). Fig. 3(a–c) illustrates that the length of SMF affect the transmission spectrum greatly, the loss is about 10–20 dB and distinction ratio is about 10–20 dB, the insertion loss is a little large and we could optimize the length of MMF or the size of up-taper to reduce the loss. It also can be seen that with the interferometer length increasing, the interference fringe spacing decreases.

It can be seen that the interference spectrum is not uniform, in order to investigate the number of propagating mode contributing in the interference process, the transmission spectrum is Fast Fourier transformed. Fig. 4 shows the Fourier transform result of Fig. 3. It is obvious that the power is primarily distributed in the core mode and a dominant cladding mode. Meanwhile, although some other cladding modes corresponding to minor frequency peaks are also excited, they exhibit weak impact on the interference pattern for lower intensities.

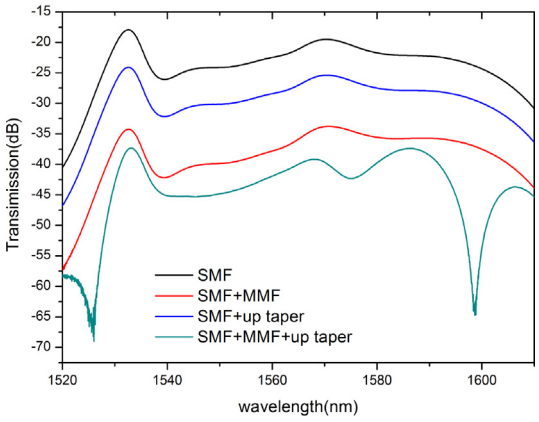


**Fig. 2.** Transmission spectra of optical source, MMF alone, up-taper alone and MMF combines up-taper.

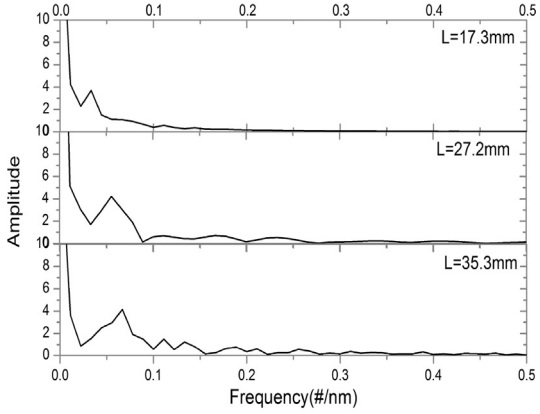


**Fig. 4.** Spatial frequency spectrum by taking the FFT for the MZ interferometer with $L$ = 17.3,27.2 and 35.3 mm, respectively.