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In-line Mach-Zehnder interferometer based on a dissimilar-doping dual-core fiber for high sensitivity strain and temperature sensing

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ABSTRACT

A dual-core fiber in which one of the cores is doped with Germanium and the other with Phosphorus is used as an in-line Mach-Zehnder (MZ) interferometer to perform high sensitivity strain and temperature sensing. Opposite sensitivities for high and low wavelength peaks were demonstrated when strain was applied. To our knowledge this is the first time that such behavior is demonstrated using this type of in-line MZ interferometer based on a dual-core fiber. A sensitivity of (78±2) pm/με, between 0-950 με and (1380±20) pm/ºC between 45 and 80ºC is demonstrated. It was also demonstrated that it is possible to use this configuration for simultaneous measurement of strain and temperature and a matrix equation to calculate them was given.

Keywords: Mach–Zehnder interferometer, Optical fiber sensors, Dual-core fiber

1. INTRODUCTION

Dual-core or two-core fibers, were first proposed as strain sensors in 1981 [1]. This type of fibers were also demonstrated as temperature sensors in 1983 [2]. With the advent of microstructured fibers, several twin-core fibers were developed such as twin-core fibers with special air cladding [3] and based on photonic band-gap fibers [4]. Hybrid dual core fibers where light is guided by total internal reflection in one core and by band-gap guidance in the other were also proposed for wavelength-selective coupling [5]. More recently, another type of microstructured dual-core fiber was developed: the suspended twin-core fiber. In this case the two cores appear to be suspended in large air holes by thin glass bridges [6]. All these configurations based on twin core fiber can be used for physical measurements. Specific solutions have been studied for temperature-independent strain sensors or for simultaneous measurement of strain and temperature.

The main advantage of using a single fiber with two cores is the stability of the interferometer, namely with the temperature. However, the stress induced during the fabrication process of this type of fiber can lead to unwanted propagation effects, e.g. birefringence. The design of the fiber also introduces relevant trade-offs: the optical coupling between the two cores can be a limitation when the two cores are close. On the contrary, when the two cores are very distant, coupling light simultaneously from a single-mode fiber to the two cores may be challenging. In this case to solve the problem, a tapered fiber splice is a convenient solution.

In this work, the authors present an in-line Mach-Zehnder (MZ) interferometer based on a dissimilar dual-core fiber used as a sensing element. The optical path is different because the two cores present different doping materials (and hence different refractive indices and different sensitivities to strain and temperature). The MZ interferometer is characterized in strain and temperature and demonstrated to be an alternative solution for simultaneous measurement of these magnitudes.

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2. EXPERIMENTAL SETUP

Fig. 1 presents the experimental configuration used to characterize the in-line MZ interferometer based in a dual-core fiber as sensing element. The configuration uses a broadband light source to illuminate the MZ interferometer. The sensing device consists in a dual-core fiber with a length of 0.32 m. The filling of the fiber was pure silica and the diameter of the cladding was 125 µm. As for the cores, one of them was doped with germanium, had a diameter of 5.1 µm, an expected Δn of 0.013 and a numerical aperture of 0.195. The second core was doped with phosphorous, had a diameter of 6.4 µm, a Δn of 0.00835 and a numerical aperture of 0.155. The distance between the two cores was approximately 14.9 µm and in both cases the cutoff wavelength was estimated at approximately 1.3 µm. An image of the transversal cross-section of the double-core fiber geometry is presented in Fig. 2. The in-line MZ interferometer is created by splicing both ends of the double-core fiber with standard single-more fiber (SMF). The core of the SMF was placed between the two cores thus minimizing the differences between the amount of light coupled into each of the cores. After the fusion splice, the fiber is tapered reducing the diameter of the fiber in the splice region to ≈60 µm (approximately half the initial size). This increases the numerical aperture and therefore the coupling of light into both cores. Since the two cores of the dual-core fiber have different refractive indices, these will present different optical paths and an in-line interferometer is created. When strain (length of the fiber is changed) or temperature (which causes a thermal expansion of the fiber) is applied to the dual-core fiber, the optical path difference between the interferometer arms (the two cores) is changed, and therefore the optical spectrum at the end of the interferometer is changed. Strain was applied to the dual-core fiber by fixing one end to a stationary stage and the other end to a micrometric translation stage on which deformations were applied at constant room temperature. As for the temperature measurements they were performed with no strain applied to the dual-core fiber. An optical spectrum analyzer (OSA) with a maximum resolution of 0.01 nm was used to interrogate the MZ in transmission.

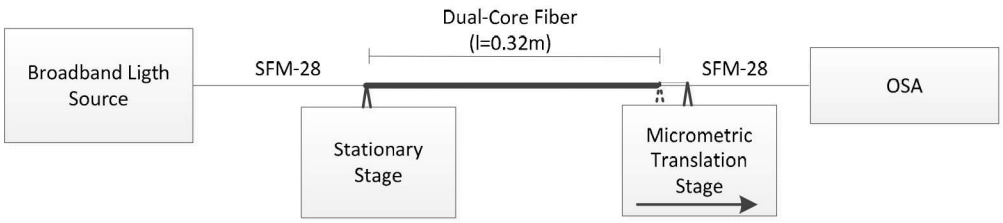

Figure 1. Experimental setup used to characterize the dual-core fiber as a strain and temperature sensor.

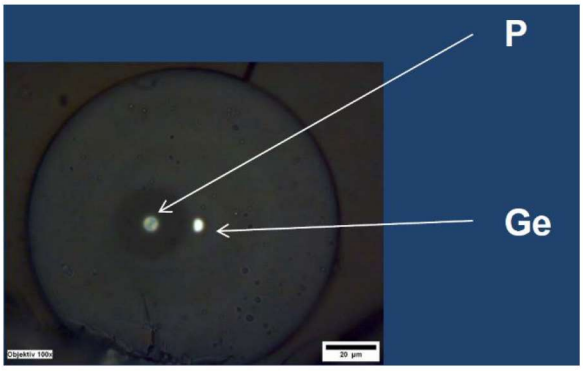

Figure 2. Cross section of the dual-core fiber, showing the germanium and phosphorous doped cores.

3. RESULTS

Fig. 3 presents the transmission spectrum of the resulting in-line MZ interferometer in non-strained conditions and the wavelength shift when a certain strain is applied. The expected dips appear in the spectral response corresponding to the MZ behavior, however their spacing is not exactly uniform, which might indicate a certain dispersion in the differential

refractive index. From the separation of these notches, an estimation of the effective index difference among the two cores can be obtained. The estimated effective index difference varies along the whole spectrum but remains always in the order of 10^{-4}. This turns out to be one order of magnitude lower than the expected difference, which might indicate that the fabrication process introduces stresses that tend to even the refractive index differences of the two cores.

In terms of strain sensitivity, the MZ peaks present opposite strain response for high and low wavelength ranges. To our knowledge this is the first time that this effect is observed in this type of in-line MZ interferometer based on a dual-core fiber. Although a more careful theoretical analysis of the sensor should be developed, this effect could be owed to a slope modification of the differential refractive index among the two cores as a function of wavelength which could be related to the differential strain sensitivity of both cores. Fig. 4 shows the wavelength shift of the peaks of the in-line MZ interferometer spectrum when a) strain and b) temperature is applied. With increasing applied strain (fig. 4a) the interference fringes are observed to move to shorter wavelengths (blue shift, $\Delta\lambda_B$) below 1520 nm and to higher wavelengths (red shift, $\Delta\lambda_r$) above 1560 nm. Sensitivities of (-96±2) pm/με ($\Delta\lambda_B$) and (78±2) pm/με ($\Delta\lambda_r$) were observed when a strain of up 950 με was applied. As for the temperature measurements (fig. 4b), all interference fringes were observed to move to higher wavelengths with increasing temperature. It was observed that the temperature sensitivity was higher for the lower-wavelength branch. Sensitivities of (1380±20) pm/ºC ($\Delta\lambda_B$) and (1110±50) pm/ºC ($\Delta\lambda_r$) were observed when the temperature was raised from 45ºC to 80ºC.

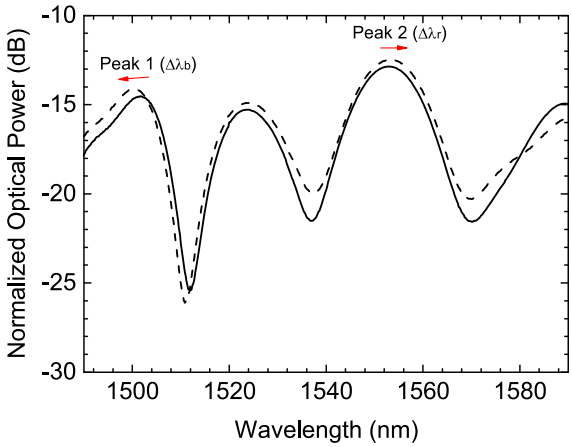

Figure 3. Shift of the normalized transmission spectrum of the in-line MZ interferometer with and without applied strain.

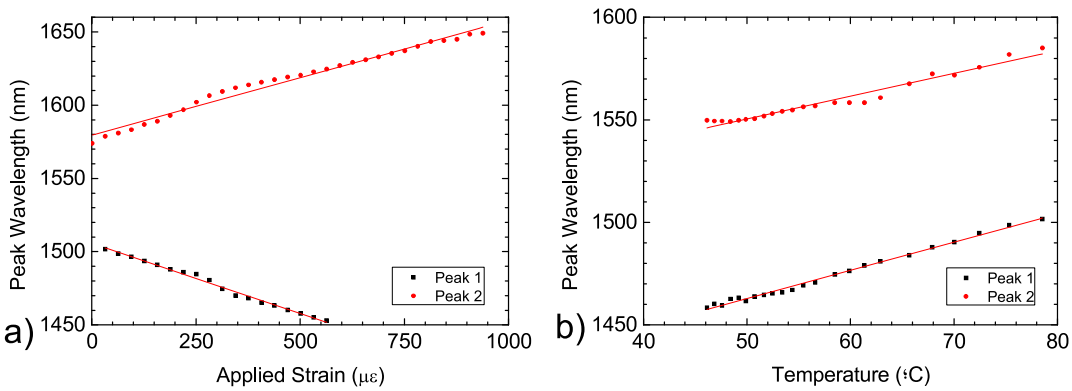

Figure 4. Peak wavelength shift of the in-line MZ interferometer spectrum as function of the applied a) strain and b) temperature.

Given the different sensitivities presented by the MZ peaks, this configuration could be used for simultaneous measurement of strain and temperature. In this case, the strain and temperature can be calculated by the following matrix equation:

$$\begin{bmatrix} \Delta T(^{o}C) \\ \Delta\varepsilon(\mu\varepsilon) \end{bmatrix} = \frac{1}{[0.2142]} \begin{bmatrix} 0.078 & 0.096 \\ -1.11 & 1.38 \end{bmatrix} \begin{bmatrix} \Delta\lambda_B(Peak_1)(nm) \\ \Delta\lambda_r(Peak_2)(nm) \end{bmatrix}$$

4. CONCLUSIONS

A dual-core fiber in which one of the cores is doped with Germanium and the other with Phosphorus is used as an in-line MZ interferometer to perform high sensitivity strain and temperature sensing. Opposite sensitivities for high and low wavelength peaks were demonstrated when strain was applied. To our knowledge this is the first time that such behavior is demonstrated using this type of in-line MZ interferometer based on a dual-core fiber. This effect was tentatively explained as a slope modification of the differential refractive index among the two cores as a function of wavelength which could be related to the differential strain sensitivity of both cores. With increasing temperature, all peaks shifted to higher wavelengths and it was observed that the sensitivity was higher for the peaks of lower wavelengths. A sensitivity of (78±2) pm/με, between 0-950 με and (1380±20) pm/ºC between 45 and 80ºC is demonstrated. Finally, it was demonstrated that it is possible to use this configuration for simultaneous measurement of strain and temperature and a matrix equation to calculate them was given.

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