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Temperature Sensor based on Vernier Effect Using Two Cascaded Capillary Hollow-Core Fiber Mach-Zehnder Interferometers

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Abstract. The purpose of this work is to report the fabrication of an exceptionally sensitive cascaded Vernier Effect-based temperature sensor using two Mach-Zehnder interferometers (MZIs). The MZIs sensors were fabricated by fusion splicing a small section of capillary hollow-core fiber (CHCF) between two, 1 mm length, segments of multimode fibers (MMFs). The laboratory results showed that the proffered sensor has a temperature sensitivity of 0.02804 nm/°C from 20 to 50 °C, while the in-line configuration shows an increment of around 67.35 times regarding the single sensor, being of 1.8885 nm/°C in a range from 20 to 60 °C. Furthermore, this sensor configuration shows a resolution of 0.0159 °C. Considering the materials used, temperature range, easy fabrication, low-weight, and low-power consumption we believe that our sensor based on the Vernier effect can be used in applications like cell culture, microfluidic microchannels, and edge computing.

Keywords: Optical fiber sensors, capillary hollow-core fiber, Mach–Zehnder interferometer, Vernier effect.

1 Introduction

The optical fiber sensors have been growing to become a meaningful and necessary technology for industry development and scientific advancement. These optical devices are appealing due to their immunity to electromagnetic interference, compact size, being lightweight and instant response. Also, fiber optic sensors can be used to test and measure a far-reaching number of physical variables among which is temperature.

All these fiber optic sensors (FOS) exploit two silica glass properties, the thermo-optic [1] and thermal expansion [2] effects to transform the changes of temperature into one of the following cases, the first case could be a wavelength shift or the second case could be power variations of the output spectrum.

One drawback of the all-fiber optic temperature sensors is their low sensitivities which make them ideal for high-temperature measurements but not adequate for low-temperature applications like in cell culture.

Different techniques have been used to overcome this disadvantage such as adding polymers [3] or nanoparticles to the fiber structures [4], they have shown good results, but the fabrication process becomes cumbersome. In the late years, the use of the Vernier effect has increased to enhance the temperature sensitivity of the fiber optic sensors, this is carried out by setting two fiber optic interferometers in parallel [5] or series [6] configuration.

In this work, we propose and demonstrate a temperature sensor built with two Mach-Zehnder interferometers (MZIs) in a series configuration (Vernier effect). The MZIs were made by fusion splicing a small piece of capillary hollow-core fiber between two pieces of multimode fiber.

2 Working Principle

2.1 Working Principle of a Single MZI

As shown below, the structure of the single MZI is made-up of a part of CHCF that is spliced between two small arts of MMFs. The dimensions of the transversal section of the CHCF are 65.5 µm for the inner diameter and 125 µm for the outer diameter. Using a broadband source of light, it is possible to inject light through the sensor and redirect it to the OSA to measure it, making use of the SMFs that are spliced to the sensor.

In previous works, a modal analysis of the MZI, to know the modes propagating in the fiber and it was found that two modes propagate in this structure [7]. The first one is the mode that travels in the hollow core made of air (the fundamental mode), and the second one is a ring cladding mode that propagates in the silica glass section. While the temperature changes, the RI of the silica glass also changes due to the TOC, giving place to temperature fluctuations and originating the wavelength shifts.

2.2 Working Principle of Two Cascaded MZIs

As aforementioned, the Vernier effect is observed when two signals are added together, to achieve this, it is necessary to set two MZIs in a series configuration, being the first sensor named as the reference and the second sensor as a sensing element. The sensing

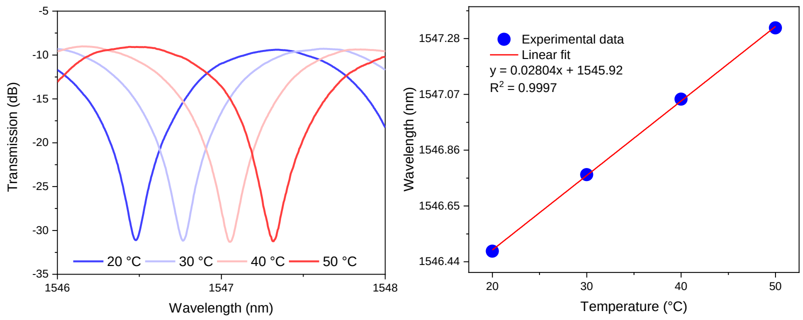

Fig. 1. Transmission spectra and wavelength shift of the MZI sensor at different temperatures.

MZI suffers the temperature variations, and the reference sensor is kept fixed at a sustained temperature. The sum (superposition) of the two signals creates an envelope. Then it is necessary to follow the wavelength shift of said envelope, allowing the measurement of temperature variations with higher sensitivities.

3 Fabrication and Experimental Results

3.1 Fabrication of a Single MZI

To begin with the fabrication of the sensors it is necessary to separate the manufacturing process into two parts. The first part of this process consists of splicing a 1 m long of SMF to a section of MMF and then cleaving the MMF to 1 mm in length.

This section is going to work as a beam splitter. After that, a section of CHCF was spliced to the MMF (beam splitter), and then the section of CHCF was cleaved to a length of 3 mm. This part of the sensor structure is set aside.

The second part requires fabricating another beam slitter (SMF + MMF), cleaving again the MMF to a 1 mm length. Finally, the part of the sensor that was set aside was spliced together with the newly fabricated beam splitter, completing the sensor.

3.2 Experimental Results of a Single MZI as a Temperature Sensor

To demonstrate that it is possible to use the Vernier Effect in a series configuration to enhance the temperature sensing capabilities of two MZI connected. It is necessary to characterize, at different temperatures, the sensitivity of the single MZI that will be used as a sensing element.

The setup consists of a light source, in our case a super luminescent diode (SLD) that injects light to the sensor using the 1 m long SMF attached to it and delivers the output transmission of the device to an OSA by the second SMF.

It is necessary to set the sensing MZI on a heating element, a Peltier cell in our case, to increment the temperature from 20 to 50 °C in little increments of 10 °C. The wavelength shift of the dip as the temperature increases shows a temperature sensitivity of 28.04 pm/ °C.

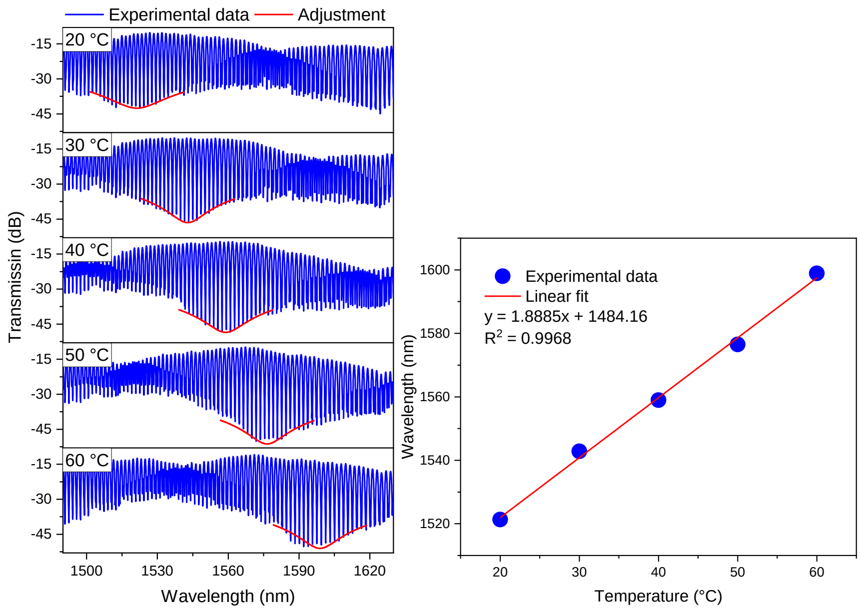

Fig. 2. Transmission spectra and wavelength shift of two cascaded MZI at different temperatures.

3.3 Experimental Results of Two Cascaded MZI Using the Vernier Effect

To test the temperature response of the two MZIs that were connected in series, it was necessary to reduce the temperature variations in the second MZI (the one used as reference). To achieve that a second heating element, with a fixed temperature, was necessary. It is worth noting that this new experimental setup works exactly like the previous one, but in this case, the sensing MZI was set on the Peltier cell, where temperature changes in steps of 10 °C, ranging from 20 to 60 °C, were made; meanwhile, the reference MZI was set on a hot plate at the fixed temperature of 30 °C.

The spectral response, as well as the wavelength shift, of the two cascaded MZIs using this configuration, is shown in Fig. 2. It is possible to observe that an interference pattern modulated with a low-frequency envelope is created. To measure the temperature sensitivity, we followed one dip of the lower envelope, obtaining its wavelength shift.

The temperature sensitivity of the two cascaded MZIs was 1.8885 nm/° C. By taking advantage of the Vernier effect, in the second experimental setup, we observed that the temperature sensitivity of the two cascaded MZIs is approximately 67.35 times higher than the sensitivity of the sensing MZI alone.

4 Conclusions

By way of conclusion, when exploiting the configuration of the cascaded Vernier effect, we demonstrated an exceptionally sensitive temperature sensor using two MZIs made entirely of silica glass. By employing this configuration, it was possible to achieve, in a range from 20 to 60 °C, temperature sensitivity of 1.8885 nm/ °C, which is approximately 67.35 times higher than the sensitivity of the MZI alone. In addition, the MZIs sensors showed an excellent temperature resolution of 0.0159 °C.

Considering the materials used, temperature range, easy fabrication, low-weight, and low-power consumption we believe that our sensor based on the Vernier effect can be used in applications like cell culture, microfluidic microchannels, and edge computing.

References

1. Komma, J., Schwarz, C., Hofmann, G., Heinert, D., Nawrodt, R.: Thermo-optic coefficient of silicon at 1550 nm and cryogenic temperatures. Applied Physics Letters, vol. 101, no. 4, pp. 041905 (2012) doi: 10.1063/1.4738989
2. Li, X., Lin, S., Liang, J., Zhang, Y., Oigawa, H., Ueda, T.: Fiber-optic temperature sensor based on difference of thermal expansion coefficient between fused silica and metallic materials. IEEE Photonics Journal, vol. 4, no. 1, pp. 155–162 (2011) doi: 10.1109/JPHOT. 2011.2181943
3. Hernández-Romano, I., Cruz-Garcia, M. A., Moreno-Hernández, C., Monzón-Hernández, D., López-Figueroa, E. O., Paredes-Gallardo, O. E., Villatoro, J.: Optical fiber temperature sensor based on a microcavity with polymer overlay. Optics express vol. 24, no. 5, pp. 5654–5661 (2016).
4. Urrutia, A., Goicoechea, J., Arregui, F. J.: Optical fiber sensors based on nanoparticle-embedded coatings. Journal of Sensors, vol. 2015 (2015) doi: 10.1155/2015/805053
5. Wang, Z., Huang, L., Liu, C., Wang, H., Sun, S., Yang, D.: Sensitivity-enhanced fiber temperature sensor based on Vernier effect and dual in-line Mach–Zehnder interferometers. IEEE Sensors Journal, vol. 19, no. 18, pp. 7983–7987 (2019) doi: 10.1109/JSEN. 2019.2916891
6. Marrujo-García, S., Hernández-Romano, I., May-Arrioja, D. A., Minkovich, V. P., Torres-Cisneros, M.: In-line Mach–Zehnder interferometers based on a capillary hollow-core fiber using Vernier effect for a highly sensitive temperature sensor. Sensors, vol. 21, no. 16, pp. 5471 (2021) doi: 10.3390/s21165471
7. Marrujo-García, S., Hernández-Romano, I., Torres-Cisneros, M., May-Arrioja, D. A., Minkovich, V. P., Monzón-Hernández, D.: Temperature-independent curvature sensor based on in-fiber Mach–Zehnder interferometer using hollow-core fiber. Journal of Lightwave Technology, vol. 38, no. 15, pp. 4166–4173 (2020)