Fiber Optic Temperature Sensor Based on Multimode Interference Effects

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Abstract. A novel fiber optic temperature sensor based on multimode interference was designed, fabricated and tested. The sensor is very simple and inexpensive since we only need to splice a section of multimode fiber between two single mode fibers. Using this device a sensing range of 25°C to 375°C is demonstrated. We should also highlight that due to the pass-band filter response of MMI devices, multiplexing is rather simple by just changing the length of the multimode section.

1. Introduction
Fiber optic sensors have good durability against harsh environments, high sensitivity, stability, high resolution, fast response and immunity to electromagnetic interferences [1]. Fiber optic temperature sensors are very important mainly in environments where the optical signal is not affected by external factors. There is also the advantage of doing remote sensing without a major effort. To date, a multitude of fiber optic temperature sensors have been demonstrated. They can be classified by their principle of operation as interferometric, grating based, or based on specialty fibers. On all cases there is always a factor of fabrication cost which is reflected in the final sensor commercial value. Therefore, there is always the need for the development of a fiber optic temperature sensor that is simple, reliable, and cost-effective.

A structure that has demonstrated to be quite simple and yet very powerful is the one based on multimode interference (MMI) effects, since they exhibit a filter response which can be used for different applications [2, 3]. When such a device is heated we have contributions which could expand the multimode fiber (MMF), as well as thermo-optic effects that modify the refractive index of the MMF. The net effect is a shift of the peak wavelength response of the device as the temperature is modified. In this paper, we propose a novel and simple fiber optic temperature sensor based on MMI effects. Using this device a sensing range of 25°C to 375°C is demonstrated. We should also highlight that due to the pass-band filter response of MMI devices, multiplexing is rather simple by just changing the length of the multimode section.
2. Device description and operation

The MMI sensor consists of a MMF section known as No-Core fiber, which is a 125 μm diameter fiber with air as the cladding, which is spliced between two single mode fibers (SMF) and is schematically shown in Fig. 1. The operating mechanism is based on the self-imaging phenomena that occur in multimode fibers (MMF), which basically replicates the field at the input of the MMF on the output of the MMF for a specific wavelength.

![Fig 1. Schematic of MMI fiber temperature sensor.](image)

The length of the No-Core fiber can be calculated using [4, 5]

\[ L_p = \frac{3L_0}{4} \]

with \( p = 0, 1, 2, \ldots \)

(1)

where \( L_0 \) is the beat length

\[ L_0 \approx \frac{4n_{MMF}D_{MMF}^2}{\lambda_0^2} \]

(2)

Here \( n_{MMF} \) and \( D_{MMF} \) are respectively the refractive index and diameter of the MMF core, with \( \lambda_0 \) as the free-space wavelength [3]. With the proper No-Core fiber length, an image is formed at the output SMF. In general, three terms will contribute to the refractive index change when the MMI fiber is heated. Using Eq. 1 we can find an expression for the change in wavelength \( \Delta \lambda \) with increasing temperature \( \Delta T \) as

\[ \Delta \lambda = L \left[ (n + \Delta n)(D + \Delta D)^2 \right] - \lambda_0, \]

(3)

Here \( \Delta L = \lambda \Delta T \) and \( \Delta D = D \Delta T \) are the increment in length and diameter respectively, with \( \Delta n = \alpha \Delta T \) as the refractive index change. The thermal expansion coefficient \( (\alpha = 0.5 \times 10^{-6}/°C) \) and thermo optic coefficient \( (\sigma = 7 \times 10^{-6}/°C) \) are used for a silica fiber [6]. As will be shown below, the dominant term is the refractive index of the core.

3. Experimental setup and results

In order to test the MMI temperature sensor we fabricated an aluminium chamber in which the sensor is inserted. Temperature changes are controlled with a hot plate, and a maximum stable temperature of 375°C was obtained. We also make sure that the fiber does not make any contact with the aluminium walls, and thus the temperature has to be monitored within the aluminium chamber. A thermocouple is inserted in the chamber through a small hole making sure that is not touching the walls. As the hot plate temperature is raised, the actual MMI temperature is acquired through the thermocouple. A schematic of the traverse section of the aluminium chamber is shown in Fig. 2.

![Schematic of the traverse section of the aluminium chamber](image)

Using equation (1), the length of the MMF is calculated to have a MMI device with a peak wavelength of 1550 nm. This is the only fabrication step that needs to be accurately controlled during the fabrication of the MMI sensor. This was performed by fixing the cleaver on a metal holder, and another plate that can be moved using a micrometer controlled linear stage. This allows control of the length of the MMF to be cleaved. After fabrication the MMI device was tested and the peak wavelength was found to be 1550.08 nm which is very close to the calculated peak wavelength.
Figure 2. Schematic of the transverse section of the aluminum chamber with the MMI sensor and thermocouple.

Figure 3. MMI temperature sensor response, Left) Spectral response as a function of temperature, and Right) Peak wavelength response as a function of temperature.

Since the MMI has a pass-band filter response, the sensor is incorporated within a typical erbium doped fiber (EDF) ring cavity laser and acts as the filtering mechanism of the laser cavity. This also helps to narrow the bandwidth of the filter and allows us to measure smaller temperature changes. The output of the ring laser is monitored using an Optical Spectrum Analyzer (OSA). Measurements were made in a temperature range from 25°C to 375°C and the spectrum was taken at every temperature interval of approximately 25°C increment. As shown in Fig. 3(left), there is a uniform wavelength shift to longer wavelengths as the temperature is increased. A total wavelength shift of approximately 4.5 nm can be observed when we reach the maximum stable temperature of 375°C. By plotting the peak wavelength at every temperature increment we obtain the results shown in Fig. 3(right). As shown here (blue line), the response is a line with positive slope. By looking at equation (3) the factor that could give a linear response with positive slope is the refractive index change. Therefore thermal expansion effect that could increase the length or diameter could be neglected. We also show the peak wavelength response as estimated from Eq. (1), red line in Fig. 3(right), which shows a very good agreement with the experimental results. As shown in the results, the sensor response has a specific peak wavelength which is related to the length of the MMF. Therefore, by just changing the length of the MMF we can have another MMI sensor with a different peak wavelength, and thus multiplexed sensing can be realized without major effort.
4. Conclusions
We proposed, implemented and tested a novel fiber optic temperature sensor based in MMI effects. The mechanism is based on the peak wavelength shift of the MMI device when the temperature is modified. Compared to other fiber-optic temperature sensors, our sensor features an extremely simple structure and fabrication process, and hence a very low cost sensor. Since we can have a different peak wavelength by just changing the MMF length, multiplexing is straightforward. By using an appropriate material, high temperature sensor should be also feasible.

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