All-Fiber Multimode Interference Refractometer Sensor

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ABSTRACT

We report on a novel all-fiber refractometer sensor based on multimode interference (MMI) effects. The operating mechanism is based on the self-imaging phenomena that occur in the multimode fiber (MMF) section, which basically replicates the field at the input of the MMF on the output of the MMF for a specific wavelength. However, the longitudinal position of this image is highly dependent on the MMF diameter (D), since there is D^2 dependence on the longitudinal position of this image. For the refractive index measurement a section of no-core multimode fiber, whose cladding is air, is surrounded by the liquid sample. The liquid sample now works as the cladding medium and as a result of the Goes-Hänchen shift the effective width (fundamental mode width) of the No-Core fiber is increased. As a result, the maximum coupling resulting from the imaging phenomena occurs at a different wavelength, and this can be used to measure the refractive index of the liquid. Using this scheme we can achieve a resolution on the order of $1x10^{-5}$ for a refractive index range from 1.333 to 1.434. The device was used here to measure refractive index in liquids, but can also be applied for measuring concentration of liquids. These sensors are promising and attractive in chemical and biotechnological applications because of their high sensitivity, immunity to electromagnetic interference, and compact size.

Keywords: Multimode Interference, MMI, Refractometer, Fiber Sensor, Refractive Index Sensor, Sensor, Optical Fiber Sensor.

1. INTRODUCTION

Measurement of refractive index (RI) is very important not only for optical based devices, but also in some industrial applications. Since there are different factors that can modify its value, such as temperature, concentration, etc, real time monitoring is particularly important. Depending on the application, the equipment required for measuring the RI may vary, but in general having a system that could be portable (low weight and size), with good sensitivity, and potential for remote measurements is the ideal RI sensor. Therefore, bulk refractometers even with good sensing range and sensitivity, might not be suitable for in situ or remote RI sensing.

Waveguide based optical refractometer sensors are very attractive due to their superior advantages, such as high sensitivity, immunity to electromagnetic interference, and compact size. Integrated sensors provide the integration of different functions, but the packaging typically increases the cost of such devices. Optical fiber refractometers (OFRs) have been investigated since they offer high resolution, low cost, the possibility for multiplexing, and light coupling is rather straightforward. OFRs have been fabricated by exposing the core of single mode fibers (SMF) or multimode fibers with different fiber tip shapes [1-3]. Although good sensitivity can be achieved, there is always the question of reproducibility when thinking for mass production of devices. Fiber gratings, either fiber Bragg gratings (FBG) or long period gratings have also been used as RI sensors [4-7]. However, in both cases having a grating engraved within the fiber is always needed which might increases the cost of the sensor. Therefore, there is a need for a simple, cost-effective, and reproducible RI sensor.

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Although multimode fiber (MMF) based RI sensors have been previously investigated, there is a particular effect that occurs in MMF that has not been explored for RI sensor. The multimode interference (MMI) effect occurs in MMF and is related to the formation of periodic images of the field coupled into the MMF. This occurs at selected locations, which can be easily found by using well know equation for the MMI effect. Therefore, if a MMF with a specific length is spliced between two SMF, light with a specific wavelength will be fully transmitted through the MMI device while others will be attenuated. If either the length or diameter of the MMF is modified, thus the MMI wavelength response is altered and this can be used for sensing applications.

In this work we demonstrate a RI sensor based on MMI effects. We use a particular MMF known as No-Core fiber which is basically a 125 μm fiber with air as the cladding. Therefore, when the MMI device based in the No-Core fiber is immersed in liquid, the optical properties of the No-Core fiber are changed. The liquid becomes now the cladding of the fiber, and thus the effective diameter of the No-Core fiber is slightly modified as a result of the Goos-Hänchen effect [8]. This is correlated with the image being formed at a different length, and then the output intensity form the MMI RI sensor is also modified. According to our measurements, the MMI RI sensor covers a refractive index range from 1.333 to 1.434 with resolution up to $1\text{x}10^{-5}$.

2. MULTIMODE INTERFERENCE REFRACTOMETER

The operational principle of the MMI refractometer is quite simple. As shown in Fig. 1, the only components required are a MMF which is spliced between two SMF.

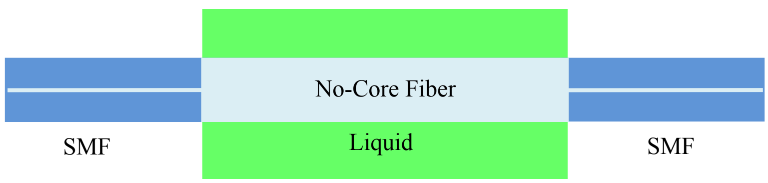


Fig. 1. Schematic of the MMI refractometer.

The MMF is the key component required to support several modes (≥ 3). After the supported modes are excited by launching a field using the input SMF, the interference between the modes propagating along the MMF gives rise to the formation of self-images of the input field along the MMF. Therefore, the length of the MMF has to be precisely cleaved in order to have a self-image right at the facet of the output SMF. The MMI effect is well known and the length of the MMF can be calculated using

$$L = p\left(\frac{3L_\pi}{4}\right) \qquad with\ \ p = 0,1,2,....., \tag{1}$$

where L_π is the beat length

$$L_\pi \cong \frac{4n_{MMF}D^2{}_{MMF}}{3\lambda_0}. \tag{2}$$

Here n_{MMF} and D_{MMF} correspond respectively to the refractive index and diameter of the MMF core, with λ_0 as the free-space wavelength. As shown in Eq. (1), self-images are periodically formed along the MMF. However, due to the nature of the MMI effect, there is a difference regarding the bandwidth observed for the true images (every fourth image) and the pseudo-images (any other image) of the input field. The pseudo-images exhibit a wider bandwidth, which is ideal for measuring wider ranges of refractive index. We can then operate the MMI RI sensor with the first pseudo-image, which give us the shortest device. If the length of the MMF is properly calculated, the experimental transmitted intensity against wavelength exhibits the behavior shown in Fig. 2. The MMI response is related to the fact that images are formed wherever the phase accumulated by the modes is a multiple of 2π, and this occur at the peak wavelength of the MMI RI sensor. As we deviate from this wavelength, phase errors between the modes are larger and thus no image is formed, resulting in a reduced signal.

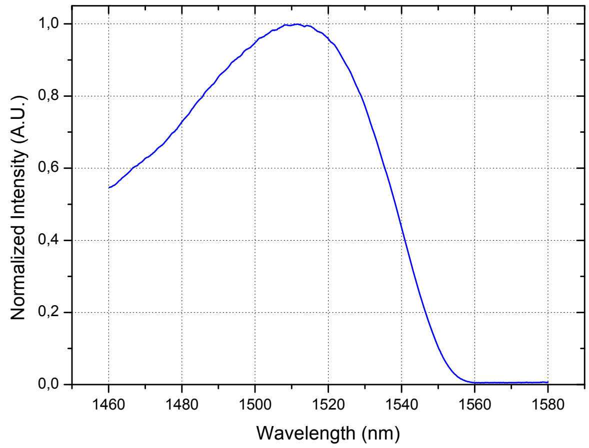


Fig. 2. Experimental wavelength response of the MMI refractometer using No-Core fiber.

By combining the MMI governing equations (1) and (2), and expressing the peak wavelength in terms of all the other parameters we obtain,

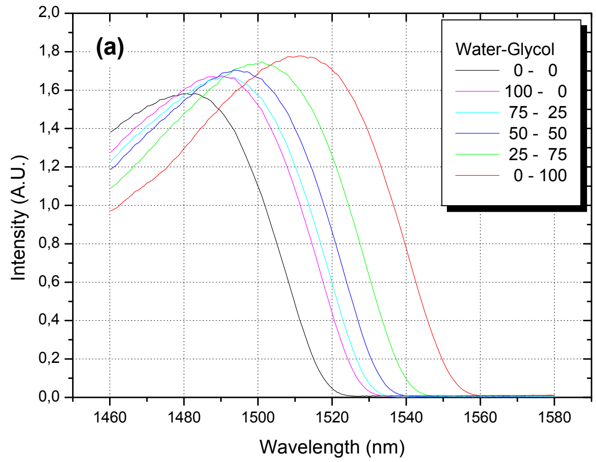
$$\lambda_0 = p\left(\frac{n_{MMF} D^2{}_{MMF}}{L}\right) \qquad with \;\; p = 0,1,2,\ldots\ldots \tag{3}$$

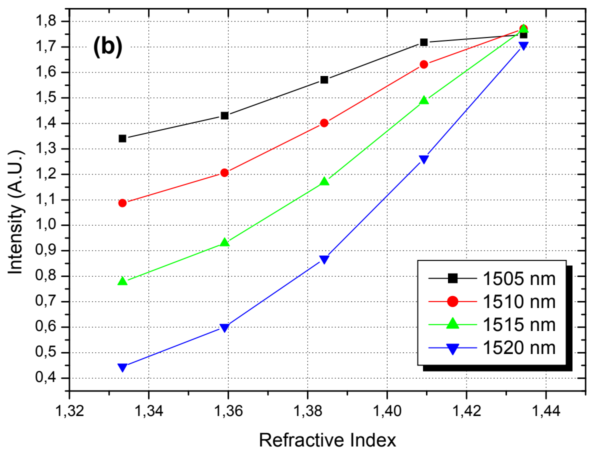
It is clear from Eq. (3) that the MMI refractometer will modify its wavelength response if the diameter of the MMF is altered. Here is where using the MMF known as No-Core fiber becomes crucial in our refractometer. As shown in Fig. 1, when the liquid is around the No-Core fiber it modifies the fiber properties since the fiber cladding is now the liquid. When the index contrast between core and cladding is reduced, the effective diameter (fundamental mode width) of the No-Core fiber is increased as a result of the Goos-Hänchen shift [8], and the wavelength response is shifted to longer wavelengths. There is also slight change of the effective index of the fundamental mode due to the overlap of the evanescent field with the liquid, which should be also taken into account when calculating the wavelength shift of the MM RI sensor. Therefore, by measuring the transmitted intensity at a selected wavelength, refractive index changes due to the liquid can be measured.

4. EXPERIMENTAL RESULTS

A No-Core fiber length of 15.42 mm was spliced between two SMF, which corresponds to a MMI refractometer with a peak wavelength of 1480 nm in air. We calculated this distance since we expect the wavelength response to be shifted to longer wavelengths. The response of the MMI refractometer was tested using light from an Agilent tunable laser (range from 1460 to 1580 nm) that was coupled to the input SMF. After passing through the MMI refractometer the light was measured using an InGaAs photodetector connected to a Keithley digital multimeter (DMM). The setup was fully controlled through GPIB ports using LabVIEW.

Measurements were performed by immersing the No-Core fiber in different mixtures of water (n=1.333) with ethylene glycol (n=1.434) at different ratios. For every liquid mixture a wavelength scan was performed in order to obtain the wavelength response of the refractometer. As shown in Fig. 3 (a), as the refractive index of the mixture is increased (glycol volume is increased) the wavelength response of the MMI refractometer is shifted to longer wavelengths. We can also observe that the shifting is not linear. This is somehow expected since there is a quadratic dependence on the diameter of the MMF. By plotting the peak wavelength for each refractive index a quadratic behavior was observed, which confirms that the shifting is due to the No-Core fiber diameter being increased. We also confirmed that by calculating the new No-Core fiber diameter using the Goos-Hänchen effect [8] as a combination of TE and TM polarizations, the wavelength shift is well described using Eq. (3).





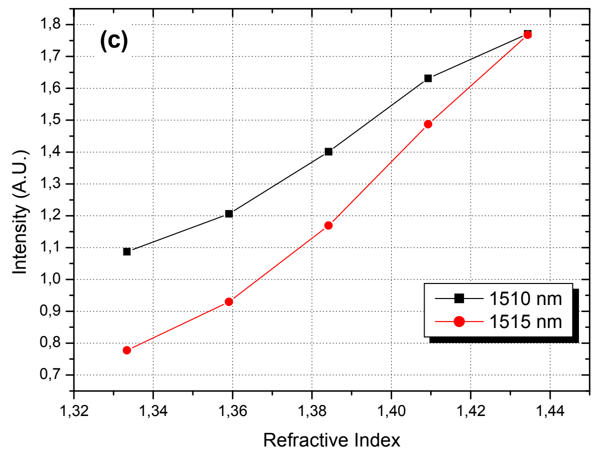


Fig. 3. (a) Wavelength response of the MMI refractometer for different refractive index liquids, (b) Transmitted intensity as a function of different refractive index liquids for specific operating wavelengths, and (c) MMI refractometer response at 1510 and 1515 nm.

Linearity is always a plus when fabricating sensors. Therefore, by fixing a particular wavelength and measuring the transmitted intensity, we can then find the best linear response. As shown in Fig. 3 (b), depending on the wavelength used, the linearity of the MMI refractometer will be slightly modified. Therefore, as shown in Fig. 3 (c), the best linear response is achieved at a wavelength of 1515 nm. Since the digital multimeter (Keithley 2700) used for our measurements has a resolution of 0.1 μV, the calculated resolution of the MMI refractometer is estimated at $1x10^{-5}$. This resolution is comparable to the best FBG-based RI sensor. The key difference is that we do not require any grating inscription, but rather being able to cleave the No-Core fiber to a specific length. We can also have multiplexed measurements by using MMI refractometers with different lengths, such that their operating wavelength in air will be different. The advantage of our MMI refractometer is that is based on cleaving and splicing fiber, and it could be used either in transmission (as demonstrated here) or reflection (using a SMF with a mirror on the facet) and a circulator or a 2x2 coupler. This allows us to operate the device for in-situ or remote measurements.

5. CONCLUSIONS

We demonstrated a novel all-fiber refractometer sensor based on multimode interference (MMI) effects. This MMI refractometer consists of a section of multimode no-core fiber with a specific length, spliced between two single mode fibers (SMF). For the refractive index measurement the section of no-core fiber, whose cladding is air, is surrounded by the liquid sample. This liquid now works as the cladding medium and as a result of the Goes-Hänchen shift the effective width (fundamental mode width) of the No-Core fiber is increased. Since the MMI effect has a quadratic wavelength dependence, a shift of the MMI refractometer response to longer wavelengths is obtained. Using this scheme a refractive index sensing range from 1.333 to 1.434 was obtained, with a resolution on the order of $1x10^{-5}$. Given the materials used for the fabrication, the MMI refractometer is an inexpensive device that can also be used for multiplexed measurements.

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