Temperature independent Refractive Index measurement using White Light Interferometry

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ABSTRACT

In this work a fiber optic interferometric system for differential refractive index measurement is described. The system is based on a white light Mach-Zehnder configuration, with serrodyne phase modulation, to interrogate two similar non-adiabatic tapered optical fiber sensors in a differential scheme. In this situation it is possible to measure the refractive index independent of temperature. Signal processing with low cost digital instrumentation developed in Labview environment allows a detectable change in refractive index of $\Delta n \approx 2\text{x}10^{-6}$, which is, from the best of our knowledge the highest resolution achieved using a fiber taper device. The results demonstrate the potential of the proposed scheme to operate as chemical and biological sensing platform.

Keywords: Fiber optic sensors, white light interferometry, pseudo-heterodyne detection, virtual instrumentation, tapers, biochemical sensing.

1. INTRODUCTION

The measurement of chemical and biological parameters in diversified environments is currently recognized as an important issue for a diversity of complex systems ranging from industrial processes, medicine and environmental applications to complete ecosystems. In this context, label free optical sensing based on the measurement of refractive index (RI) represents an interesting solution. Such approaches do not interfere with the analyte properties and require, instead, the design of sensitive layers that experience a refractive index change in its presence. This can be achieved by using biomolecules with a natural affinity to the target, or chemical species having analyte specific ligands. The combination of such membranes with refractive index sensors can therefore provide attractive solutions for biochemical sensing [1].

Fiber optic sensors, in particular, are an interesting solution due to their high sensitivity, small size, and capability for in-situ, real-time, remote, and distributed sensing. Several schemes for refractive index sensing using optical fibers have already been proposed. Surface plasmon resonance (SPR) is one of the most common [2], non-adiabatic fiber tapers [3], core exposed fiber Bragg grating (FBG) [4], long period gratings (LPG) [5], LPG based interferometers [6]. These reported works present high sensitivity to the surrounding refractive index. Nevertheless, all of these configurations are also temperature sensitive. The influence of temperature must be accounted when the RI measurement is carried out for high sensitivity detection of biological or chemical parameters, however, most authors claim to have a temperature stabilized system. Nevertheless, the water thermo-optic coefficient is $\sim 10^{-4}$ at 25ºC. This means that for RI measurements to be performed with a resolution around 10^{-6} the temperature of the sample should be controlled to better than 0.01ºC, which is very hard to do.

White Light Interferometry (WLI) has been used for remote measurement of diverse parameters such as strain, temperature and pressure [7-9]. This technique uses low coherence optical sources providing absolute measurement at high resolution and the ability of multiplexing sensors onto a single optical fiber using coherence multiplexing [10, 11]

In this work an interferometric readout system, controlled with virtual instrumentation, is described where a Mach-Zehnder white light system is used to interrogate two similar non-adiabatic fiber tapers in a differential arrangement. In this configuration it is possible to measure the refractive index with high resolution and independent from temperature.

The results demonstrate the potential of the proposed scheme to operate as a high resolution label-free bio-chemical sensing platform.

2. PRINCIPLE AND EXPERIMENT

Figure 1 shows the setup of the readout interferometer. A standard fiber optic Mach–Zehnder interferometer is used. In one of the arms, through a circulator, an open air path is implemented using a GRIN lens and a mirror mounted in a translation stage, which can be tuned to match the optical path difference of the sensing devices. On the other arm, an electro-optical phase modulator (APE from JSDU) was inserted for carrier generation, where a sawtooth modulation with its amplitude adjusted to obtain a 2π phase excursion, suitable for pseudo-heterodyne processing, is used. The coupling ratio of the first coupler was chosen in order to maximize the fringe visibility of the interferometer. Due to high insertion loses of the phase modulator (4dB) compared with the open air path (2dB), a coupling ratio of 70:30 is used. The two output ports of the readout interferometer are used to interrogate two similar interferometric sensors. Using one of the interferometers as reference and the other as sensor, and since the Mach–Zehnder outputs are in phase opposition, most environmentally induce phase drifts can be canceled out, and the phase difference between both signals depends only on the modulation inferred by the parameter of interest allowing a very stable and accurate phase measurement retrieved using phase comparison software.

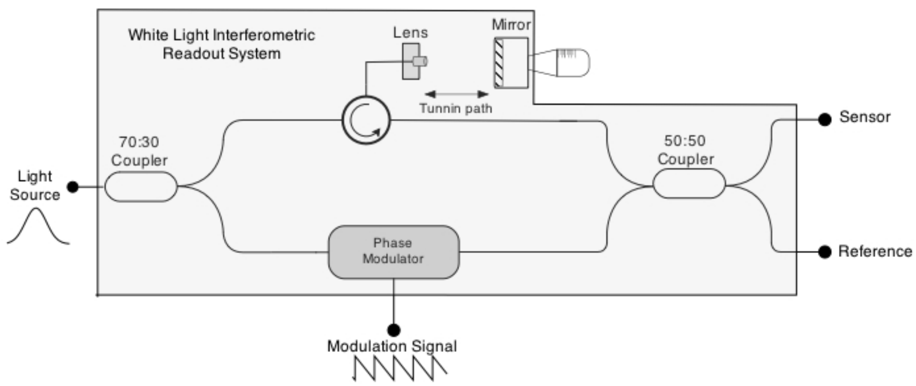

Figure 1 Readout interferometer interrogation device

The interferometers used as sensing devices were non-adiabatic tapered optical fibers (NATOF). The non adiabatic fiber tapers can be done in such a way that coupling occurs primarily between the fundamental mode of the un-pulled fiber and higher order modes of the taper waveguide, where due to the large difference of the refractive indexes of air and fiber cladding, the taper normally supports more than one mode. The light propagates at the air—cladding interface of the tapers waist region in which case the SMF is converted into a multimode waveguide. The result of back and forth coupling between the single mode of the fiber and the two (or more) modes of the taper is an oscillatory spectral response. The efficiency of this last coupling is dependent on the relative phase of the participating modes. Therefore, a NATOF behaves as Mach-Zehnder modal interferometer (conceptually it is shown in the figure 2 (a) and (b)). When there are only two modes, the relative phase is $\Delta\varphi=\Delta\beta L$, where $\Delta\beta$ and L are the difference in propagation constants of the two modes and the interaction length along the taper, respectively. Therefore, the spectral response of the taper will shift correspondingly by changing the above terms. For instance, if the RI of the surrounding environment of the taper changes, the difference in propagation constants and the relative phase would be modified leading to a shift of the spectral response. It is thus obvious that one can build sensitive RI sensors based on the NATOF.

Figure 3 shows the experimental setup for differential measurement of refractive index. The readout interferometer was illuminated by a SLD source ($\Delta\lambda_{FWHM}\approx80$ nm and $L_{coherence}\approx15$ μm). A sawtooth modulation signal (1 kHz) with amplitude 7.2 V generated by a signal acquisition board (DAQ NI 6259 USB) was applied. Two similar NATOF connected to its output ports were used. The sensing devices were fabricated with heat pulling method using a CO_2 laser. The experiment was performed using NATOFs with a taper length around 15 mm and an average taper waist diameter in the range of 6–8 μm.

The sensing elements were placed into a test chamber with both fiber ends properly fixed to avoid strain/curvature cross-sensitivity. The reference element was inside of a metallic capillary tube, thereby sensitive to temperature changes in the solution but insensitive to the external refractive index variations. The transmitted signal was guided towards two photodetectors plugged into an acquisition board. In this situation, after adequate filtering, the changes in the surrounding refractive index output arise as a phase shift on the sinusoidal carrier signal, which is retrieved using the phase comparison software.

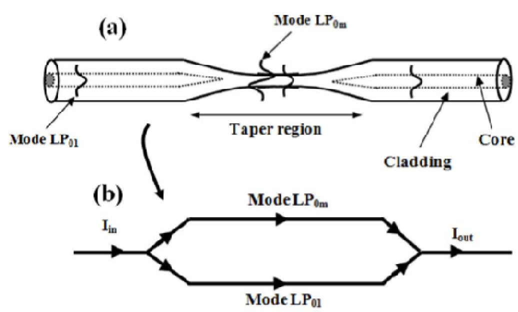

Figure 2 (a) Schematic representation of non-adiabatic taper. (b) Conceptual representation as a modal Mach–Zehnder interferometer.

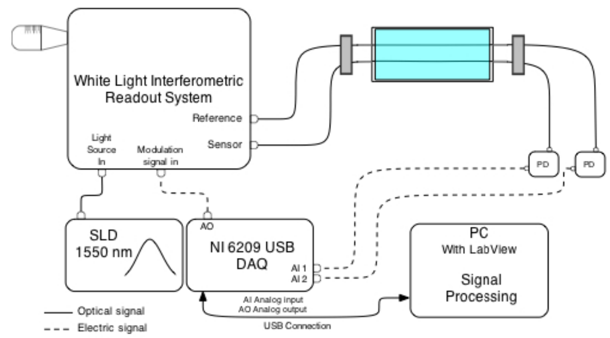

Figure 3 Setup for differential measurement of refractive index using readout interferometer.

3. RESULTS AND DISCUSSION

The response to the surrounding RI was studied by exposing the sensing head to different solutions of distilled water mixed with different concentrations of ethylene glycol to provide the RI standards in a range between 1.3355 – 1.3485. The liquid samples were previously characterized by an Abbe refractometer using the sodium D line (589 nm). The necessary adjustments, considering the sensing head operation at 1550 nm, can be made using the Cauchy equation with the respective coefficients [12]. The real time response of the differential sensing platform to surrounding refractive index step changes (SRI) is shown in figure 4. The results show, as expected, an increment in the phase difference with the increase of the SRI. From this data a calibration curve can be obtained that is showed in figure 5. A sensitivity of 57407º RIU^{-1} can be estimated from this data. The inset in figure 4 shows with more detail the phase difference fluctuation for a change in SRI from 1.3475 and 1.3454. From this information, and considering a resolution determined by 2σ, where σ is the standard deviation, divided by the sensitivity, an average resolution of $\pm 2\text{x}10^{-6}$ was calculated.. This value is, from the best of our knowledge the highest resolution achieved using a fiber taper device. In addition, in the best measurement obtained a resolution of $\pm 8\text{x}10^{-7}$ was achieve indicating the potential of this configuration to attain the highest resolution. Furthermore, it should be stated that these results were obtained with no temperature control of any kind. A drift in excess of 1ºC was measured without any observable impact in the RI measurement, demonstrating the system robustness to perform high resolution temperature independent measurements.

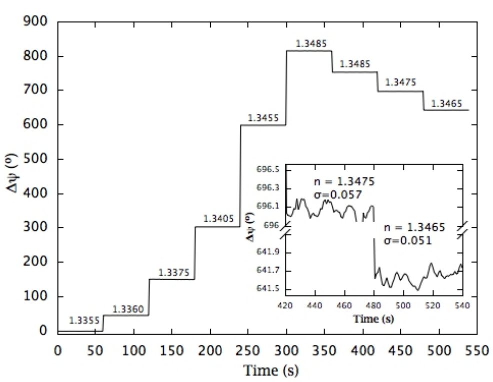

Figure 4 Time response of the sensing system to external refractive index changes.

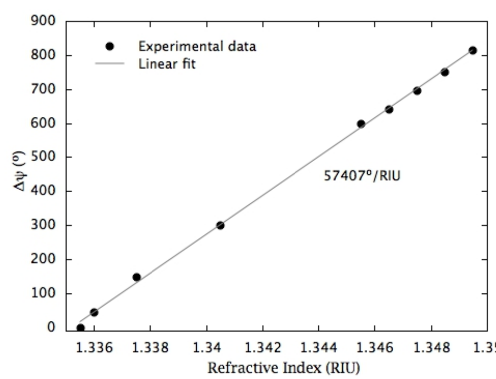

Figure 5 Calibration curve of the system for refractive index variations.

The small variations observed in the resolution calculated in different intervals of refractive index are probably due to actual refractive index fluctuations arising from heterogeneity in the dissolution of ethylene glycol in water. This is partially confirmed by the fact that highest resolution values were obtained for the solutions were the concentration of ethylene glycol was smaller. Also further improvements are possible by improving the interrogation interferometer stability. Having a birrefringent element inside the interferometer (the phase modulator) introduces some polarization dependent noise. Therefore, active polarization control, or alternative way of modulate the interferometer phase, can potentially improve the results obtained.

4. CONCLUSION

In this work a differential interferometric scheme for interrogation of fiber optic interferometric refractometers was implemented. Differential measurements of refractive index were carried out using two similar NATOFs. One of the tapers was used as sensor and was exposed to variations of SRI and temperature and a second taper was used as a reference and exposed only to the thermal variations in the sample chamber. The sensing system was characterized in the range between 1.3355 and 1.3485. A sensitivity of 57404º RIU^{-1} was estimated and an average resolution of $\pm 2 \times 10^{-6}$ was achieved ($\pm 8 \times 10^{-7}$ in the best case). It was demonstrated, by the sensitivity and resolutions obtained that the proposed configuration is a sensing system with very high performance for label-free sensing applications. In biosensing applications, the reference can be functionalized with a passive layer enabling, therefore, to compensate for temperature, bulk refractive index and even non-specific binding events enabling a truly self-referenced biosensor.

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