Fiber modal Michelson interferometers with coherence addressing and heterodyne interrogation

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Abstract. A long-period-grating-based fiber optic Michelson modal interferometer with coherence addressing and heterodyne interrogation is studied as a sensing structure for measuring environmental refractive index, temperature, and liquid level. The effects of several system parameters on the measurements are investigated. Experimental results show that the sensitivity to the external refractive index increases with the order of cladding mode and with a reduction of the fiber diameter. The decrease of the fiber diameter from 125 μm down to 70 μm enhances the sensitivity to the external index by a factor of 2.7. It is also shown that the use of a silica-core fiber increases the sensitivity to the external index by a factor of 1.4 and reduces the thermal sensitivity by a factor of 2.5 compared to a standard fiber. [DOI: 10.1117/1.2903089]

Subject terms: long-period grating; modal interferometer; refractive index; coherence addressing; heterodyne interrogation.

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1 Introduction

The measurement of chemical and biological parameters in diversified environments is recognized to be an increasingly important challenge for optical sensing technologies.[1] From this point of view, the use of optical fibers as intrinsic sensing elements is very promising due to their small size and the possibility for remote and multiplexed operation.[2]

Optical fiber sensing of biochemical measurands relies on two fundamental concepts, namely spectroscopy (fluorescence and absorption) and evanescent field interaction.[3–5] The latter is based on the partial overlap of the evanescent guided electromagnetic wave with a medium whose refractive index depends on the measurand. These changes can be measured with high accuracy using interferometric schemes. Therefore, focus has been placed on R&D of optical fiber interferometric configurations that maximize the sensitivity of light to variations of the medium refractive index and minimize the intrinsic sensitivity to other parameters, mostly temperature. Within this context, modal interferometers are very attractive, particularly those with the reference path along the fiber core and the sensing path associated to a specific cladding mode excited by a long-period grating (LPG). The most common structure of this type is based on the Mach-Zehnder configuration: a pair of LPGs is impressed down the fiber to induce interference between the core and the selected cladding mode.[6] This interferometric device is appealing for environmental sensing not only because of its reduced thermal sensitivity (the thermo-optic coefficients of the core and cladding modes are not substantially different), but also because to a certain extent it is possible to tune the device

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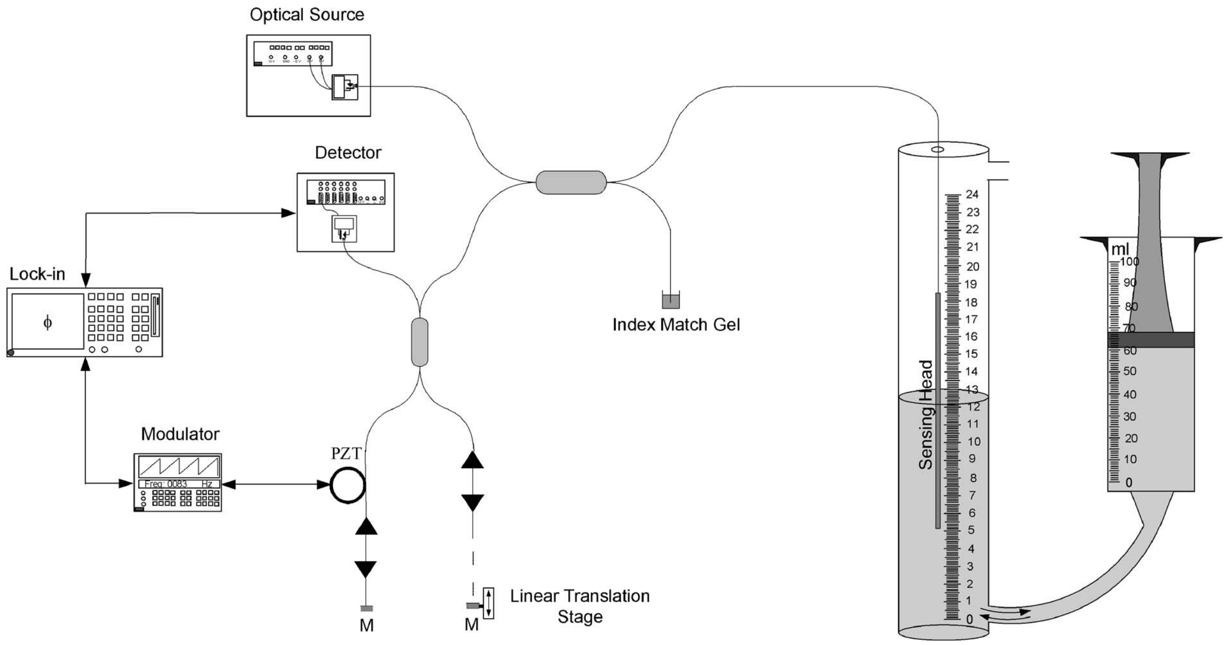

Fig. 1 Experimental setup showing the implemented interferometric interrogation scheme.

sensitivity to the refractive index variations of the fiber-surrounding medium by selecting the order of the cladding mode to be excited.

It is also possible to have an LPG-based modal interferometer in a Michelson configuration if the light is forced to cross a single LPG twice by mirroring the fiber end face after the grating. This structure, which was proposed and studied by Swart et al.,[7,8] is attractive in view of its simplicity (operation in reflection) and increased interaction length, but also because it shows a better adequacy for sensor multiplexing in several situations. Therefore, in this work we explore further the intrinsic properties of this sensing structure for environmental refractive index, temperature, and liquid level measurement. The effects of selecting different cladding modes, of etching the fiber, and of using silica-core fibers are studied in the context of sensitive phase demodulation using an interferometric heterodyne interrogation approach. Looking forward to multiplexing applications, the fiber modal interferometer is addressed in coherence through the utilization of a receiver Michelson interferometer that supports the required optical signal processing for heterodyne interrogation.

2 Experimental Setup

The experimental setup is represented in Fig. 1. Light from a super-luminescent diode (SLD), operating at 1320 nm with a FWHM spectral width of ~35 nm (coherence length $L_c \approx 33\ \mu$m), is injected into the fiber system. After crossing a 50-50 routing coupler, roughly half of the input power is guided to the LPG-based fiber modal Michelson interferometer (Fig. 2). The LPG couples a fraction of the light to a specific cladding mode, whereas the remaining light keeps propagating in the fiber core. At the fiber end a silver thin film reflects the light back to the LPG, which again induces cross-coupling between the core and cladding modes. In particular, the light that returns down the lead fiber has contributions from the light that propagated in the core and in the cladding modes at the sensing region, which accumulates a differential optical path delay (much larger than L_c) that is dependent on the measurand action. The resulting output spectra, with a characteristic interferometric modulation, can be observed in Fig. 3.

To detect the phase changes in the fiber Michelson modal interferometer, a second interferometer was built to implement coherence reading.[9,10] This is a conventional fiber Michelson interferometer with an open air path in one of its arms, which is adjusted to match the optical path difference of the sensing interferometer. The fiber in the other arm of the receiving interferometer is wrapped around a ring-shaped piezoelectric transducer (PZT) that is modulated with an electrical sawtooth waveform whose amplitude is adjusted to obtain a signal at the photodetection suitable for pseudo-heterodyne processing. After adequate electronic filtering, this signal has the form of an electric carrier (~90-Hz frequency) with a phase that mirrors the optical phase of the tandem interferometric system. This pseudo-heterodyne processing technique is known to provide sensitive interferometric phase reading.[11,12]

The LPG was fabricated in-house using the electric-arc technique described by Rego et al.[13] The period of the refractive index modulation was 439 μm, a value chosen to produce a resonance wavelength at approximately

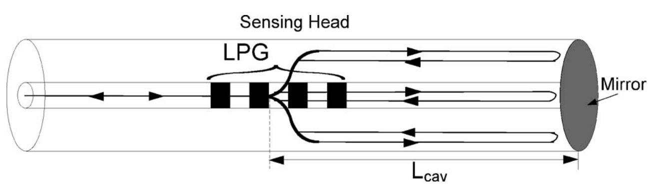

Fig. 2 Schematic of the LPG-based fiber modal Michelson interferometer.

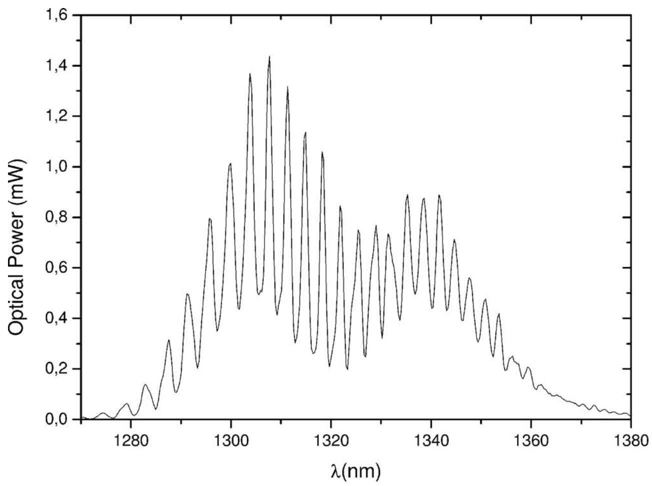

Fig. 3 Phase-encoded output of the LPG-based Michelson interferometer for a cavity length of 150 mm.

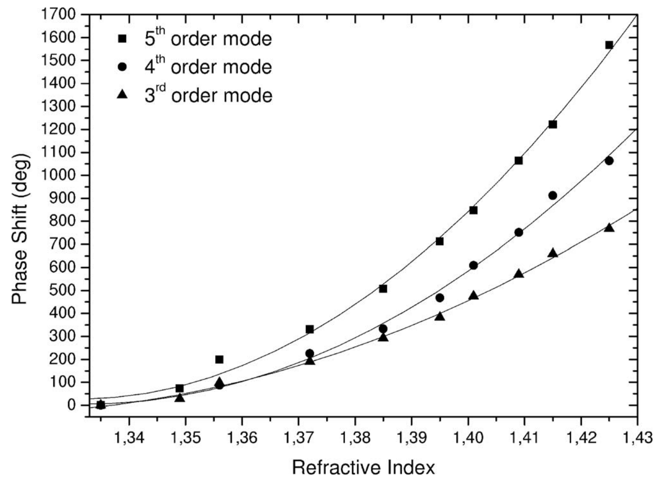

Fig. 5 Interferometric phase changes due to refractive index variations for a 150-mm sensing length and excitation of the 3rd-, 4th-, and 5th-order cladding modes.

1320 nm. This resonance wavelength corresponds to the 4th-order cladding mode. To have access to other cladding modes with resonances that match the SLD central wavelength, other gratings with periods of 475 μm and 395 μm were fabricated to correspond to the 3rd- and 5th-order cladding modes, respectively. The normalized transmission of the LPG spectrum with a 395-μm period is shown in Fig. 4. The length of the sensing fiber was ~150 mm, measured from the middle of the LPG up to the mirrored fiber end. To further evaluate the effect of the cladding diameter, two additional sensing heads with a length of 90 mm and operating with the 4th-order cladding mode were fabricated and one of them was etched with hydrofluoridric acid (HF) to reduce the fiber diameter from 125 μm down to 70 μm.[14] The whole length of the cavity was immersed in a 40% HF solution for 10 minutes. After the etching period, the fiber was thoroughly washed with dionized water, dried, and observed under the microscope. It could be confirmed that the etching procedure introduced a step reduction of the fiber diameter. While the diameter reduction should allow an enhanced sensitivity, some losses will be introduced due to the abrupt transition of the step profile. Nevertheless, at this stage, step etching was used as a simple way to assess the influence of the diameter in the interferometer sensitivity. Furthermore, in an optimized system the loss could be minimized by changing the fiber diameter in an adiabatic fashion, as was done in Ref. 14. Finally, a sensing head was fabricated in a silica-core fiber (Oxford Electronics, SMPS 1300-125 P:Dcore=9 μm, Dclad=125 μm, and NA=0.11), where a LPG with a period of 730 μm was impressed (90-mm sensing length). The refractive index profile of this fiber is described by Rego et al. in Ref. 15. In all cases, the fiber buffer layer was previously removed.

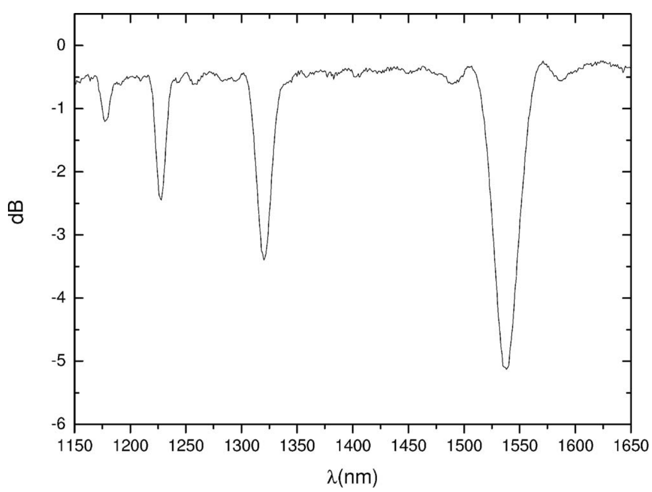

Fig. 4 Typical transmission loss spectra recorded in a SMF-28 fiber with the electric arc technique (Λ=395 μm).

3 Results and Discussion

The sensing characteristics of these different structures were studied, particularly for the measurement of the refractive index of liquids, but also for the measurement of the liquid level and temperature. The schematic of the setup used for these measurements is shown in Fig. 1. In all experiments, contact between the LPG and the liquid was prevented to avoid shifting the LPG resonance band. Any large shift in the LPG resonance would hinder the use of coherence addressing and the pseudo-heterodyne processing technique to provide the interferometric phase reading. In a practical system, this limitation could be easily overcome by assuring proper packaging of the LPG.

To assess the system sensitivity, the interferometric sensing head was submitted to changes in the external refractive index in the range 1.33 to 1.42 using the setup in Fig. 1. Changes in the external refractive index were obtained by immersing the interferometer in samples of water combined with different percentages of ethylene glycol. The refractive index of the different samples was calibrated using an Abbe refractometer with the sodium D line (589 nm). This test was repeated using a LPG with different periodicities. Figure 5 shows the sensitivity of the 3rd-, 4th-, and 5th-order cladding modes to the external refractive index variations. The sensitivity to the external refractive index increased with the order of the cladding mode. For instance,

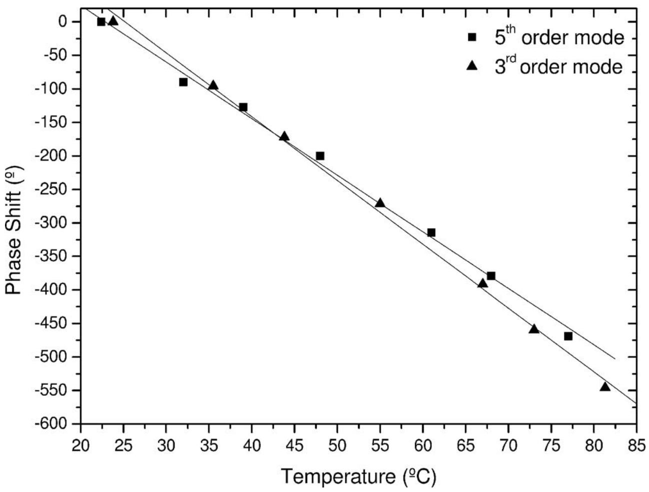

Fig. 6 Phase shift as a function of liquid temperature for a 150-mm sensing length and excitation of the 3rd- and 5th-order cladding modes.

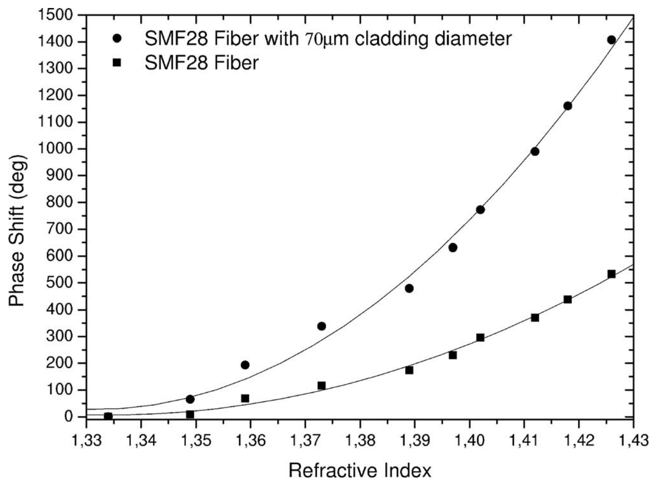

Fig. 7 Interferometric phase changes due to refractive index variations for a 90-mm sensing length and two different sensing head fiber diameters of 125 μm and 70 μm, respectively.

in the refractive index region around 1.41, values of $\sim 1.31 \times 10^4$ deg/riu, $\sim 2.14 \times 10^4$ deg/riu, and $\sim 2.67 \times 10^4$ deg/riu were obtained for the 3rd-, 4th-, and 5th-order cladding modes, respectively.

It was mentioned before that one advantage of fiber modal interferometers is their reduced sensitivity to temperature when compared with standard fiber interferometers. To confirm this statement, the phase variations induced by changes in the temperature of the liquid were registered for the sensing head with 150 mm and operating with the 3rd- and 5th-order cladding modes. Figure 6 shows that the temperature sensitivity is similar for both modes and is $\sim 9\,^\circ$C. When normalized to the fiber length, this translates into a sensitivity of ~ 63 deg/($^\circ$C·m). This reduced value results from the intrinsic differential operation of the fiber modal interferometer. For comparison, the temperature sensitivity of a standard single-mode Michelson interferometer is ~ 10313 deg/($^\circ$C·m), a value substantially higher (in both cases, the normalization length refers to "fiber length").[16]

To evaluate the possibility of tuning the system sensitivity, sensing heads were fabricated using a fiber with a different external diameter. A diameter reduction was achieved by submitting the standard fiber to etching with 40% HF. Figure 7 illustrates the enhancement to the measurement sensitivity when the fiber diameter was reduced. The fiber with an external diameter of 70 μm had a sensitivity response improved by a factor of ~ 2.7 when compared with the 125-μm standard fiber.[14] The readout system resolution was determined by using the results given in Fig. 8, which shows the phase output of both interferometers as they were successively immersed in solutions of the growing refractive index. When changing between solutions, the phase acquisition was paused while the fiber was thoroughly rinsed with dionized water. From the phase steps obtained for the indicated refractive index variations, the average standard deviations of the phase output, $\Delta\phi$, could be estimated. The minimum detectable value was given by $2\Delta\phi$, and resolution values of 9.0×10^{-5} and 4.6×10^{-5} were obtained for the standard and etched fibers, respectively, in the refractive index region around 1.42. These figures where obtained for a system bandwidth of 78 mHz.

The use of silica-core fiber as a valuable alternative to germanium-doped standard fibers was also investigated. Figures 9 and 10 show the sensitivity of the sensing head to the refractive index and temperature, respectively, for silica-core and SMF 28 fibers with a sensing length of 90 mm. It is clear that, compared to the standard SMF 28 fiber, the silica-core fiber enhances the sensitivity to the refractive index variations by a factor of 1.4 in the refractive index region around 1.41. Another positive effect of using the silica-core fiber is the extra reduction of the sensing head thermal sensitivity by a factor of ~ 2.5.

In view of the system's sensitivity to refractive index variations, the configuration shown in Fig. 1 was also tested for the measurement of the liquid level. To simulate this functionality, the sensing length was immersed gradually into the water, and the phase variation was registered accordingly. Figure 11 shows the results for a sensing length of 150 mm and considering the excitation of different cladding modes. Figure 12 shows the results for a sensing

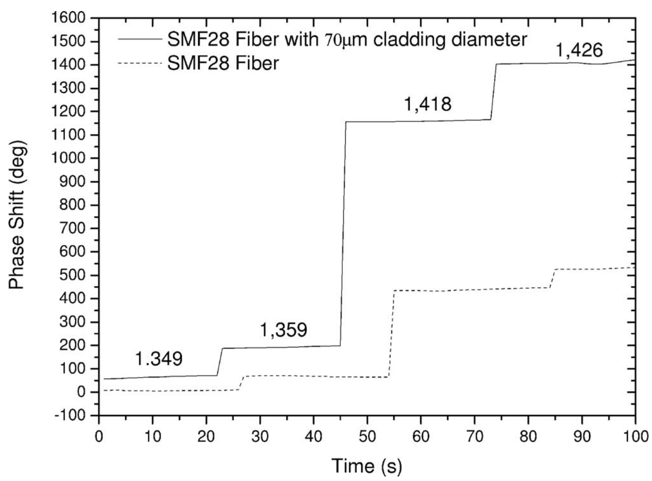

Fig. 8 System response to step changes in the refractive index.

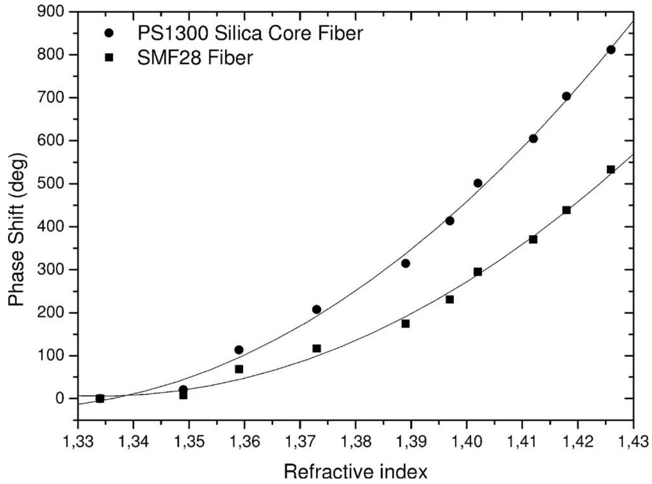

Fig. 9 Comparison of sensing system phase changes due to refractive index variations using a silica-core fiber and a SMF 28 fiber (sensing length of 90 mm).

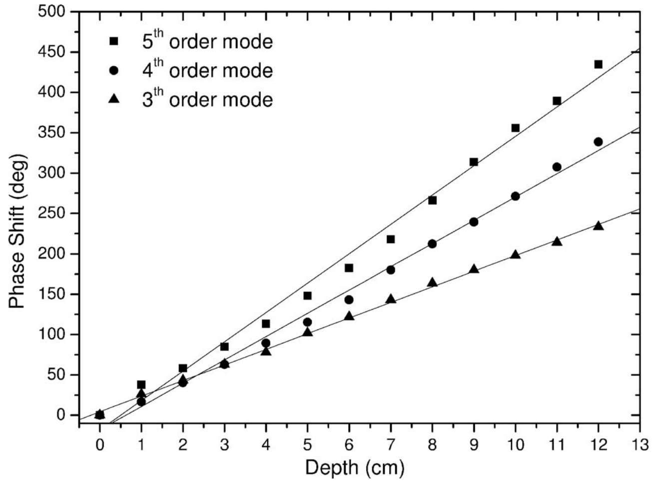

Fig. 11 Interferometric phase as a function of sensing fiber immersion depth in water for different cladding modes of the SMF 28 fiber (sensing length of 150 mm).

length of 90 mm and considering the effect of different fiber diameters and the utilization of the silica-core fiber.

The most direct feature that can be obtained from the analysis of Figs. 11 and 12 is the linear dependence, in all situations, of the interferometric phase on the immersion depth. As expected, the sensitivity increases with an increase of the cladding order mode that is excited by the LPG. Indeed, as shown in Fig. 11, sensitivity slopes of 1.9 deg/mm, 2.9 deg/mm, and 3.6 deg/mm were obtained for the 3rd-, 4th-, and 5th-order cladding modes, respectively. On the other hand, Fig. 12 indicates that the use of the silica-core fiber increases residually the sensitivity to a value of 3.3 deg/mm (as compared to 3.0 deg/mm for the standard SMF 28 fiber), but the largest effect appears when the sensing length is etched. The reduction of the fiber diameter from 125 μm to 70 μm increases the immersion depth sensitivity to a value of 8.2 deg/mm. Overall the results show that sensor sensitivity can be tuned with some versatility. In particular, fiber etching allows for great sensitivity enhancement. Swart recently reported a sensitivity of 2.67 deg/mm for a liquid-level sensor using a similar LPG-based Michelson interferometer.[8] Because a different interrogation scheme was used, and the cladding mode order was not given, a direct comparison with the results presented here is not straightforward. Nevertheless, it can be seen that, in terms of absolute device sensitivity, either increasing the mode order or etching the fiber produces higher sensitivities than in Ref. 8.

4 Conclusions

This work reports on an investigation of the sensing properties of LPG-based fiber Michelson modal interferometers addressed in coherence and interrogated using the heterodyne phase detection technique. The target measurement parameters investigated were the refractive index of liquids surrounding the sensing fiber, their temperature, and the

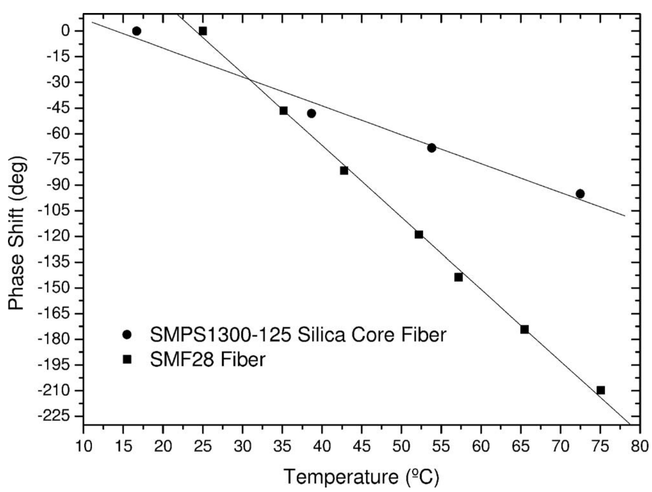

Fig. 10 Comparison of sensing system phase changes due to temperature variations using a silica-core fiber and a SMF 28 fiber (sensing length of 90 mm).

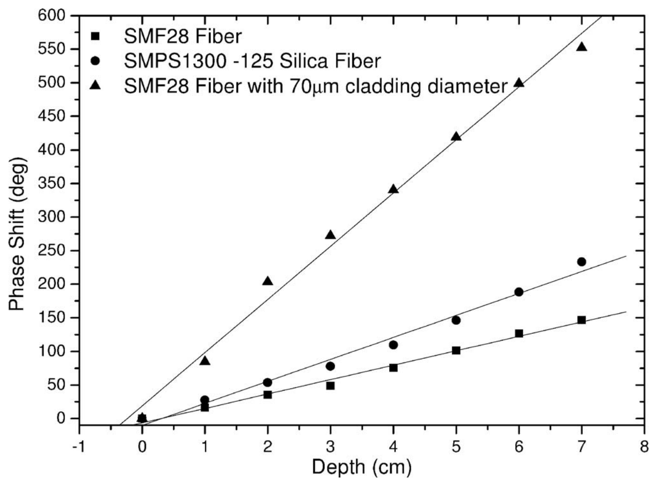

Fig. 12 Interferometric phase as a function of sensing fiber immersion depth in water for a standard SMF 28 fiber, the SMF 28 with cladding layer reduced to 70 μm, and a SMPS1300-125 silica-core fiber (sensing length of 90 mm).

liquid level. The effects on the measurand readout sensitivity of the order of the excited cladding mode and of the diameter of the cladding layer were researched, as well as the influence of employing a silica-core fiber in the sensing length instead of a standard single-mode fiber.

The experimental results demonstrate the possibility of tuning the sensitivity and operation range of this sensing platform through simple changes in the sensing head geometry. This versatility will allow users to optimize the performance of biochemical sensors that rely on refractive index measurements by matching the system sensitivity to the biochemical-induced refractive index changes. Geometrical tailoring of the SMF 28 fiber will thus provide a versatile solution for a wide range of refractometric sensing applications. To obtain higher sensitivities, high-order modes and reduced fiber diameters are recommended. While an increase in sensitivity is also achievable with a silica-core fiber, its use is particularly attractive in cases where thermal insensitivity is required. The results obtained demonstrate a sensing system with high-performance operation that is an interesting option for remote measurement of a large range of parameters, particularly biological and chemical parameters.

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