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Abstract. A multimode interferometer based-fiber optic sensor with a silica tube section aimed to measure refractive index (RI) variations of surrounding liquids is presented. The sensing head is a silica tube section fusion spliced to single mode fibers operating in transmission. In the splice regions tapers were made to allow the light to be guided in the silica tube while the core is formed by air. This configuration permits measurements of refractive index variations with sensitivities of 101.1, 106.29, and 107.97 nm/RIU considering resonances with different wavelengths. The same resonances were tested with temperature variations with sensitivities achieved of 7.8, 8.7, and 9.3 pm/ °C, respectively. The spectral variation associated with one degree temperature change corresponds to a refractive index change of $\sim 8 \times 10^{-5}$, proving the low temperature dependence compared with sensitivity to RI variations. [DOI: 10.1117/1.3646393]

Subject terms: multimode interference; optical fiber sensors; refractive index; temperature.

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1 Introduction

Optical fiber-based refractive index (RI) sensors with multimode interference (MMI) has been studied and developed as an attractive optical device due to their desirable advantages, exhibiting a pass band filter response, high sensitivity, immunity to electromagnetic interference, small size, and low cost.[1,2] The ease of fabrication and the excellent properties, like unique spectral characteristics, turned them suitable for signal transmission and optical sensing applications directed to the measurement of, temperature, strain, curvature, or RI.[3–5] Typically, the MMI-based device consists of a step-index multimode fiber (MMF) section spliced between two single mode fibers (SMFs) forming SMF-MMF-SMF structures. The multimode interference occurs in the MMF section which can be influenced by the external perturbation. When the light input from SMF enters the MMF section, high-order modes of MMF are excited and generate a field profile that changes along the MMF section and along the direction of propagation. At a fixed position on the optical axis the optical spectrum shows well-defined resonance loss peaks. The coupling efficiency between the two opposite sides of the MMF section depends on the wavelength, fiber parameters, and the length L of this section.[6] By choosing different lengths of an MMF section it is possible to adjust the wavelength position and the spectral characteristics of the resonances, as well as their number in a spectral window of a specified width.

Yung et al. had studied one sensing head using a small length of silica tube fusion-spliced between two SMFs where the leaky mode through the hole and the diverging radiation along the pure silica cladding form a Mach–Zehnder interferometer.[7]

The present study uses a silica tube as a multimode fiber section creating a multimode interference by the injection of light directly in the silica cladding, and the sensing head scheme is presented in Fig. 1. Two single mode fibers are fusion spliced to a section of silica tube with length L, external diameter of 125 μm, and an inner hole with 20-μm diameter. With all fibers aligned, the taper technique is used on both splices to maintain the light guided through the silica tube. The first taper allows the light to be injected into the silica tube in a symmetric way due to the shape and position of the hole. With the second taper it is possible to collect the exit light with acceptable loss. With this structure there is an air core and the light is guided in the silica tube wall which is surrounded by the trapped air in the inner hole and the external liquid, both with lower RI.

The sensing head was illuminated with an ASE broadband source and it was placed slightly stretched into a recipient with an aqueous solution with an RI that could be changed, 0.046 RIU up to 1.3915 RIU, by adding small quantities of ethylene glycol. The sensing head is constituted by the tapers and the silica tube and both were immersed in the aqueous solution. The light was collected with an optical spectrum analyzer with a resolution of 0.05 nm. The spectra for these variations are presented in Fig. 2 showing different wavelength resonances λ_1, λ_2, and λ_3 for $L = 8.5$ cm [Fig. 2(a)] and λ_4 and λ_5 for $L = 17$ cm [Fig. 2(b)]. These resonances are similar to reject bands, which mean residual light at these wavelengths is coupled to the output SMF. In the presence of external refractive index changes a red shift of these resonances is observed when the change is toward the increase of the refractive index.

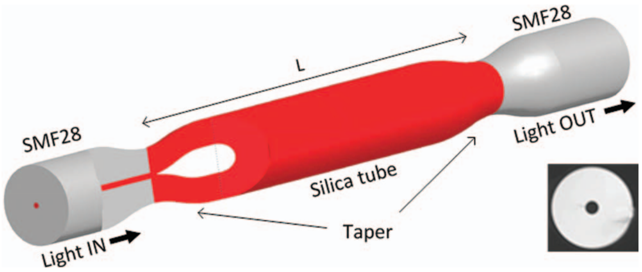

Fig. 1 Schematic diagram of the measurement setup with a section of silica tube spliced and tapered between two single mode fibers. Inset is a top view of the silica tube.

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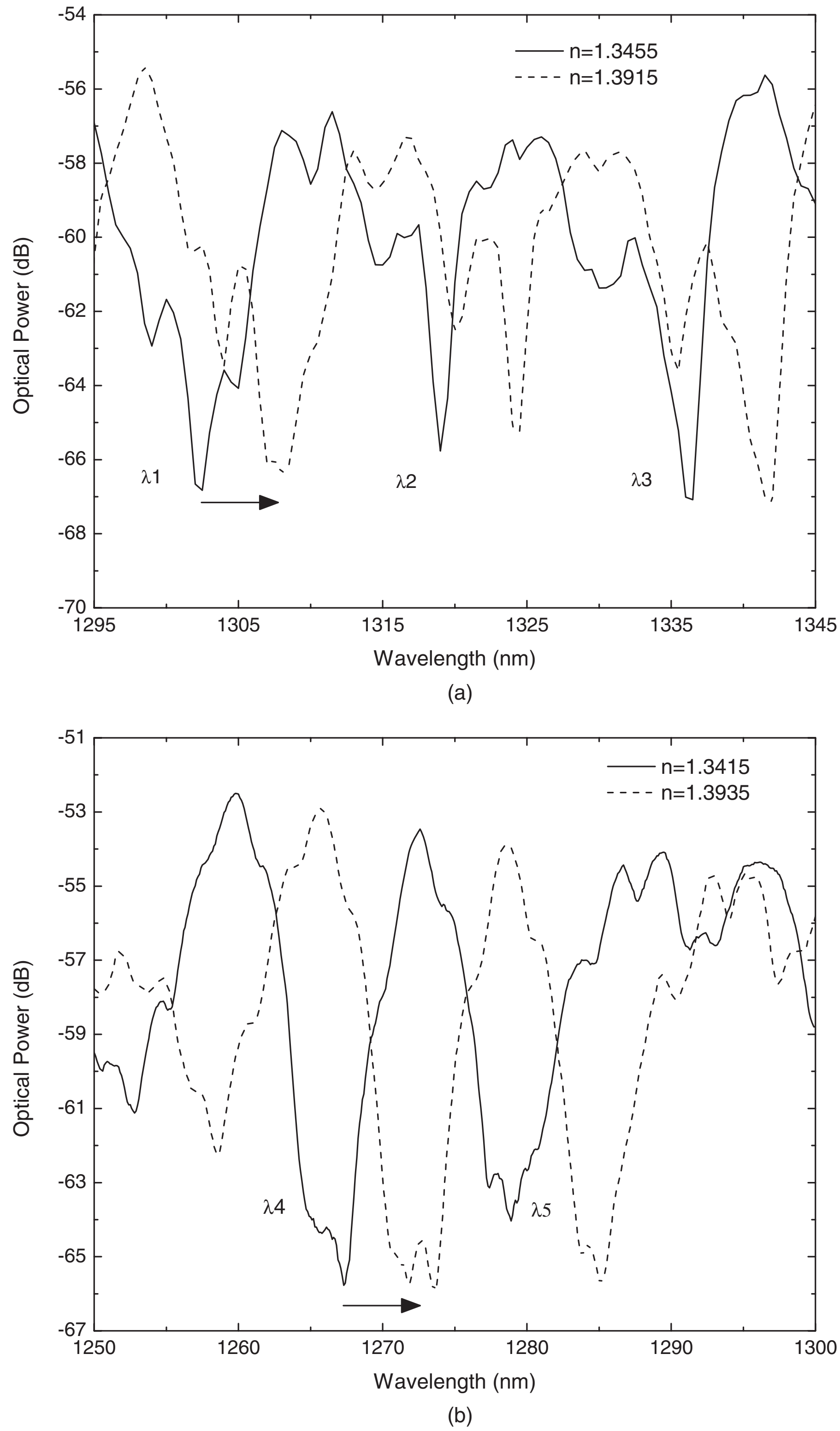

Fig. 2 Optical spectra obtained with two different lengths: (a) $L = 8.5$ cm for a refractive index variation of 0.046 RIU, and (b) $L = 17$ cm for a refractive index variation of 0.052 RIU.

The sensing head was immersed in the liquid. The response for the sensing head with $L = 8.5$ cm with RI variations is presented in Fig. 3. The sensitivity reached was 101.10, 106.29, and 107.97 nm/RIU for λ_1, λ_2, and λ_3, respectively. Different temperature responses were also observed and quantified applying with an electric oven to the sensing head a temperature variation in air from15°C up to 200°C. The results are shown in Fig. 4, from where temperature sensitivities come out of 7.8, 8.7, and 9.3 pm/°C for resonances λ_1, λ_2, and λ_3, respectively. These sensitivities are lower compared with those obtained when the MMI structure is implemented with step index multimode fiber[8] and

Table 1 Comparison of the sensitivity results for refractive index and temperature variation using $L = 8.5$ cm and $L = 17$ cm.

		Refractive index		Temperature	
		Wavelength (nm)	Sensitivity (nm/RIU)	Wavelength (nm)	Sensitivity (pm/°C)
$L = 8.5$ cm	I1	1303	101.1	1278	7.8
	I2	1320	106.3	1295	8.7
	I3	1337	108.0	1317	9.3
$L = 17$ cm	I4	1266	111.1	1275	6.6
	I5	1279	112.1	1280	8.5

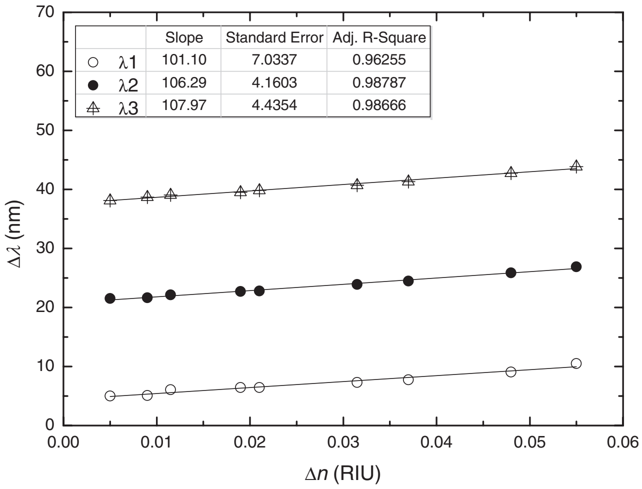

Fig. 3 Refractive index response considering λ_1, λ_2, and λ_3.

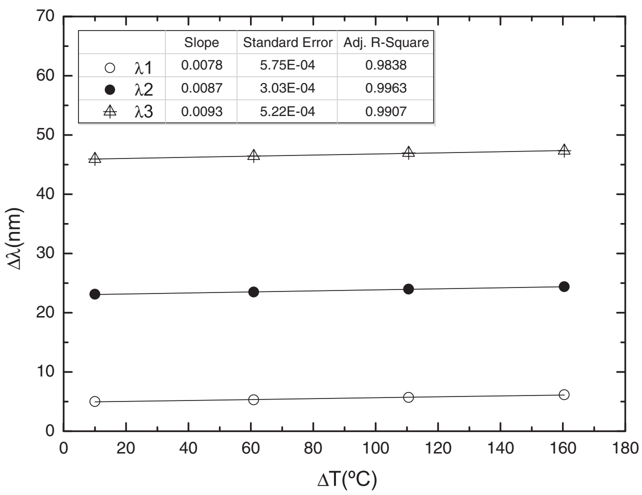

Fig. 4 Temperature response considering λ_1, λ_2, and λ_3.

lower than that obtained by Yung et al. [52 pm/°C (Ref. 7)], favoring the overcome of the temperature cross-sensitivity problem. Indeed, a variation of 50°C induces a spectral variation equivalent to the one observed when the refractive index of the external medium changes 4×10^{-3}, illustrating the dominant role of this parameter in the spectral shifts of the sensing structure researched in this work. Actually, it was observed that this characteristic is more pronounced when using the silica tube instead of a silica rod with the same external diameter and length, a topic that is the subject of further investigation.

Above 200°C changes in the spectrum of the sensing structure besides the lateral shift, particularly the decrease of the visibility are observed. A possible explanation for this behavior grounds on the rearrangement of the silica structure in the taper section when the temperature increases, with the consequent change of the coupling efficiency single mode fiber-silica tube.

A comparison of the sensitivity results for refractive index and temperature variation using $L = 8.5$ cm and $L = 17$ cm is presented in Table 1.

2 Conclusions

In this research a silica tube-based sensing structure was proposed and characterized, which contains input and output single mode fibers, originating a multimode interference behavior with high surrounding refractive index sensitivity and comparatively low temperature cross-sensitivity, indicating the utility of this sensing head as an optical refractometer.

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