Journal of the European Optical Society - Rapid Publications 4, 09041 (2009) www.jeos.org

Refractive index tip sensor based on Fabry-Pérot cavities formed by a suspended core fibre

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A Fabry-Perot refractometer based on the suspended core fibre is presented. The Fabry-Perot cavities are formed by a section of suspended core fibre between conventional single-mode fibres. This miniature refractive tip sensor is demonstrated for the measurement of the refractive index change by measuring the fringe visibility and through the analysis of the fast Fourier transform. The two methods are compared. The temperature dependence was also characterized. [DOI: 10.2971/jeos.2009.09041]

Keywords: Fabry-Pérot cavities, optical fibre sensor, refractometer

1 INTRODUCTION

The assessment of refractive index (RI) is becoming very important in biological or chemical applications due to fact that several substances can be detected directly or indirectly through RI measurements. For this purpose, several methods have been developed using different types of optical fibre sensor configurations. In 1983, Cooper demonstrated a refractive index measurement combining two technologies where one of them was based in an optical fibre [1]. Asseh proposed a chemical etched fibre Bragg grating (FBG) refractometer [2], and Patrick fabricated long period grating refractometers in different types of optical fibres [3]. These two last technologies for measuring refractive index are based on the wavelength shift of the fibre structures. Other alternative solutions use the Fresnel reflection at the fibres' cleaved end. Recently, a Fabry-Pérot fibre optic sensor for liquid refractive index measurement was described. The Fabry-Pérot interferometer is achieved using the reflected Bragg peak of a short FBG and the reflections from the cleaved end of a fibre (Fresnel reflection) that is in contact with the measurement sample [4]. Another configuration was also studied by Rao *et al.* and consists in a fibre-optic refractive-index sensor which is based on an intrinsic Fabry-Pérot interferometer formed by a section of endlessly single-mode photonic crystal fibre (PCF) and conventional single-mode fibre [5].

In this work, for the first time to our knowledge, the authors present a Fabry-Pérot refractive index tip sensor based on a suspended core fibre. The cavities are formed using a suspended core fibre between single mode fibres with the last section of the single mode fibre being cleaved and sensitive to the external physical parameter. To read the refractive index tip sensor, the fringe visibility and a fast Fourier transform (FFT) analysis were both used. The sensing head was also characterized in its temperature behaviour.

2 EXPERIMENTAL RESULTS

Figure 1 shows the experimental setup of the refractometer using Fabry-Pérot cavities with a suspended core fibre. The sensing head was illuminated by a broadband source with a range of 100 nm (C-band). An optical circulator was used to interrogate the Fabry-Pérot cavities in reflection. The measurements were taken by an optical spectrum analyser (OSA) and through appropriate computer software the analysis of the FFT was performed. The sensing head was formed by three cavities since the two main cavities form in conjunction a third one (inset of Figure 1). The first physical cavity is formed with a suspended core fibre between the single mode fibres. The second physical cavity is formed by the section of single mode fibre between the suspended core fibre and the end of the fibre. The last cavity results from the conjunction of the two main cavities. The first physical cavity is used as a cavity reference because is isolated from the refractive index of the liquids. This cavity is based on a suspended core fibre made of

Received April 07, 2009; published August 28, 2009 ISSN 1990-2573

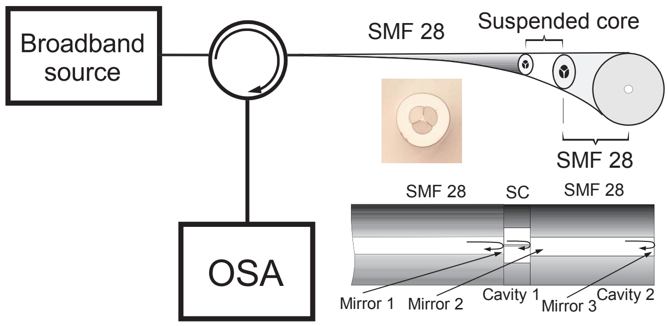

FIG. 1 Experimental setup of the refractive index tip sensor.

pure silica and fabricated at IPHT (Institute of Photonic Technology, Jena, Germany). The suspended core fibre is formed by three holes with diameters of 20.2 μm, while the core and the cladding have diameters of $\approx$ 3.2 μm and $\approx$ 129 μm, respectively (inset of Figure 1). The length of the first physical cavity is approximately $L_1 = 210$ μm. The second physical Fabry-Pérot comprehends a standard single mode fibre (SMF 28) with a cavity length of $L_2 = 1.24$ mm. The last cavity, corresponding to $L_1 + L_2$, is the cavity used for the refractive index measurement.

Figure 2 presents the spectral response of the refractive index tip sensor when is in the air and in the water, respectively. In the spectral response, two main modulations superimposed are observed resulting from the conjunction of the cavities transfer functions. The higher spatial frequency corresponds to the cavity formed from the main cavities, and is in contact with the external refractive index. The main amplitude modulation of the spectral response corresponds to the cavity formed by the suspended core fibre. Figure 2(a) shows also that only the visibility of the spectral response is changed when the refractive index varies (air and water) while no alteration of the phase is noticeable. In order to analyse the behaviour of the sensing head in the spatial frequency domain, Figure 2(b) shows the FFT of the spectral response, being possible to associate the spatial frequency peaks to the respective cavity lengths [6]. The first peak (Peak 1) corresponds to the suspended core cavity and does not change with the RI of the liquids being, therefore the reference peak. Peak 2 corresponds to the second physical cavity (SMF 28), is also sensitive to the external refractive index but presenting lower amplitude change, due to asymmetry of the two mirrors. Peak 3 corresponds to the total cavity $L_1 + L_2$ which is sensitive to the external medium. To determine the refractive index, a R parameter is defined as the optical power ratio between the signal (Peak 3) and the reference (Peak 1), being therefore independent of the optical power source fluctuations. To calibrate the RI tip sensor, the tip was immersed in samples of water combined with different percentages of ethylene glycol. The liquid samples were characterized through an Abbe refractometer using the sodium D line (589 nm). Because the RI tip sensor was operated at 1550 nm window, it was necessary to use the Cauchy equation with the respective coefficients [6].

Figure 3 shows the spectral responses of the sensing head for different liquid refractive indices. It can be seen that the visibility changes with the alteration of the RI liquids and the

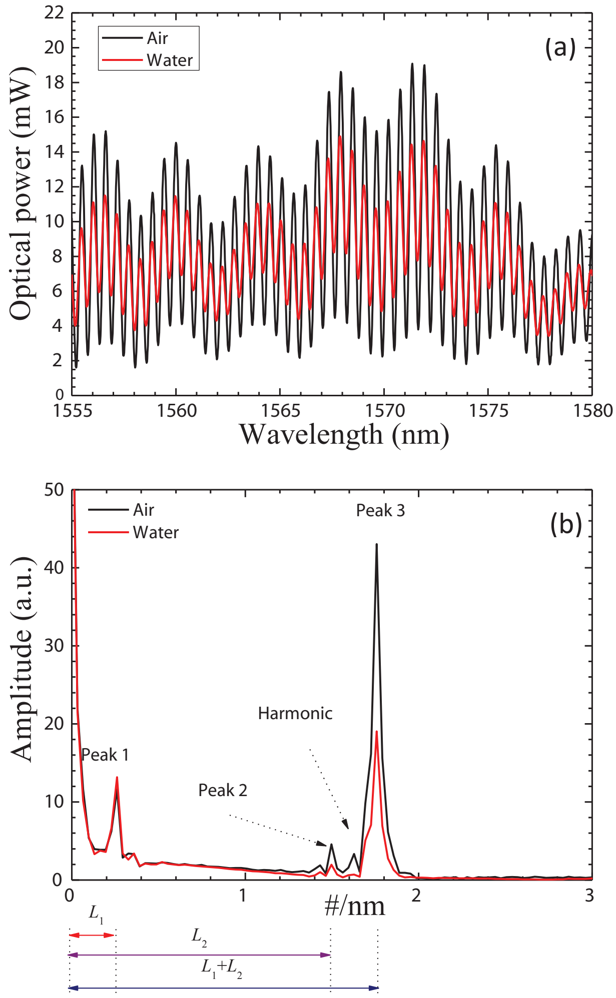

FIG. 2 (a) Spectral response when the sensing head is in the air and in the water, respectively. (b) FFT result of the two spectral responses.

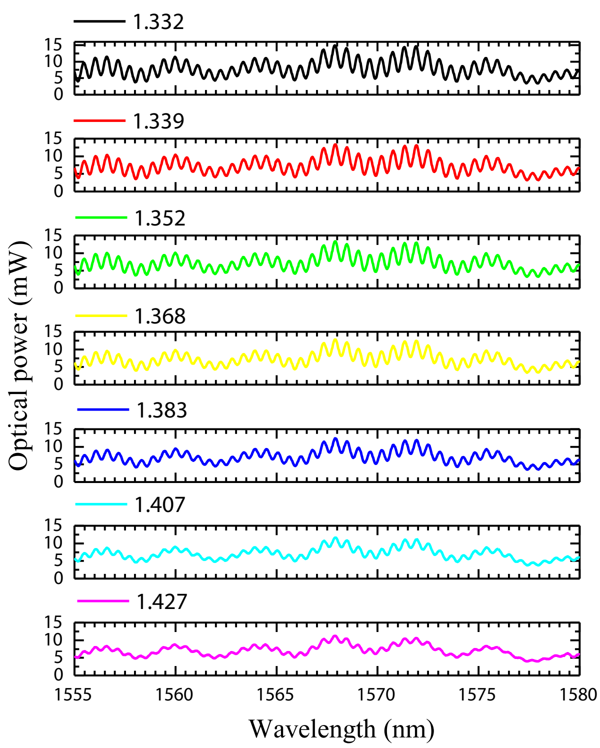

FIG. 3 Spectral responses of the sensing head for different liquid refractive indices.

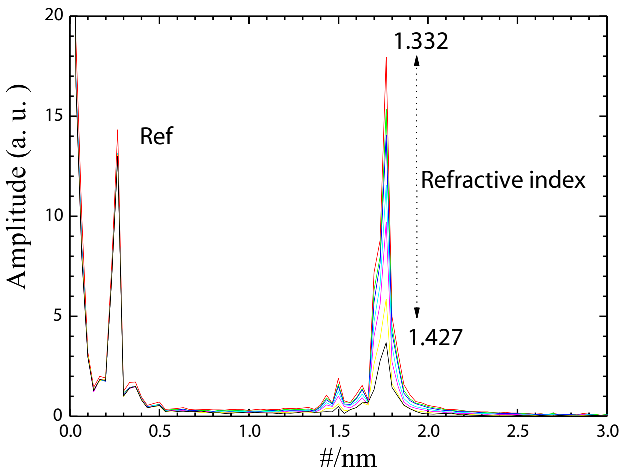

FIG. 4 FFT result of the RI tip sensor for different liquid refractive indices.

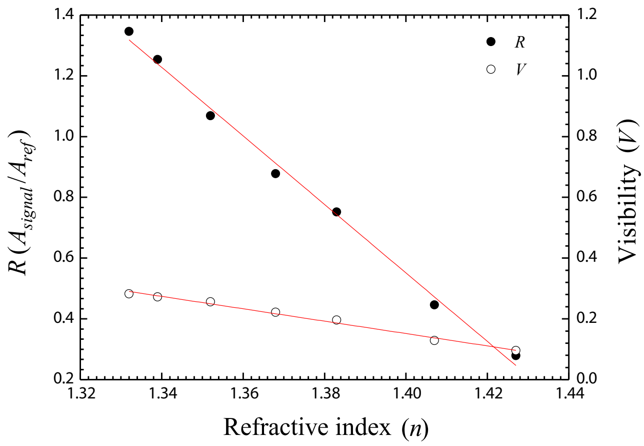

FIG. 5 Variation of the parameter (R) and visibility (V) with refractive index of the liquids.

phase is maintained constant. The spatial frequency components were calculated by the FFT for all spectral responses obtained by the different refractive index variation. The reference is constant and the signal decreases with the increase of external RI (see Figure 4).

Figure 5 shows the relationship between refractive index and the ratio between the amplitude signal and the reference. The refractive index sensitivity obtained by the FFT technique is -11.27 ± 0.34/RI with a resolution of 2×10^{-4}.

This result was also compared with the visibility measurement. In this case it is necessary to calculate the power reflection coefficients at mirrors 1, 2 and 3 denoted as R_1, R_2 and R_3, respectively [7]. R_1 and R_2 are equal and $R_3 = \left[(n_{\text{SMF}} - n_{\text{Liq}})/(n_{\text{SMF}} + n_{\text{Liq}})\right]^2$. The visibility can be easily obtained using the following equation [7],

$$V = \frac{2\sqrt{R_1}\,(1-R_1)\,(1-\alpha_1)\,(1-\alpha_2)\left(\frac{n_{\text{Liq}}-n_{\text{SMF}}}{n_{\text{Liq}}+n_{\text{SMF}}}\right)}{R_1 + (1-\alpha_1)^2\,(1-\alpha_2)^2\,(1-R_1)^2\left(\frac{n_{\text{Liq}}-n_{\text{SMF}}}{n_{\text{Liq}}+n_{\text{SMF}}}\right)} \quad (1)$$

where α_1 and α_2 are the transmission loss factors at the respective mirrors The reflectivity of mirror 1 is similar to the reflectivity of mirror 3 because the core area of the suspended core

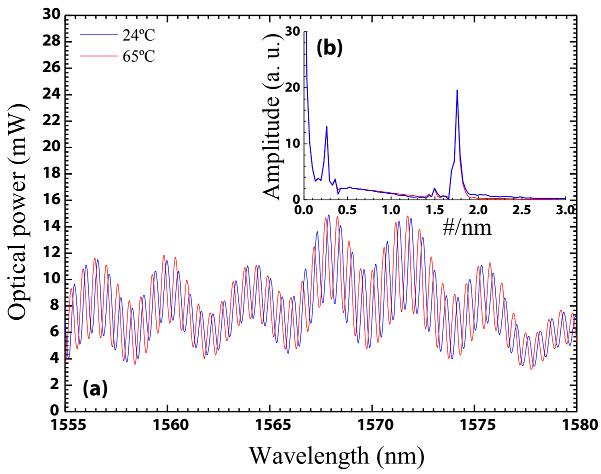

FIG. 6 Experimental results of the RI tip sensor when temperature was applied for 24 °C and 65 °C, respectively, for (a) spectral response and (b) FFT analysis.

is very small when compared with the core area of the SMF 28, being possible to consider in both cases the Fresnel reflection values. On the other hand, the reflectivity of mirrors 1 and 3 is higher than mirror 2, since the interface of doped silica/air presents a higher reflectivity when compared with the interface of doped silica /pure silica.

Figure 5 also presents the visibility ($V = I_{Rmax} - I_{Rmin}/I_{Rmax} + I_{Rmin}$, where I_R is the total reflective intensity in the maximum and minimum values) of the RI tip sensor. For this case, using the visibility equation, the sensitivity is lower with a value of -2.03 ± 0.09/RI with a resolution of 7×10^{-4}. Comparing these two methods, the FFT technique presents more sensitivity since the translation of the spectral response to the spatial frequency domain allows the decomposition of the spectral response in different spatial frequencies and consequently enables the measurement of a single spatial frequency with higher sensitivity.

The RI tip sensor was also characterized in temperature. The refractometer was immersed in water and was heated up to 65°C. Figure 6 presents the two spectral responses of the sensing head for two temperatures (24°C and 65°C, respectively). For high temperature, the cavities' lengths change due to the thermal expansion of the material and for this case the FFT can also be used to measure the cavity length change [7]. Figure 6(a) shows the spectral response of the RI tip sensor for the two different temperatures. In this situation, the phase changes with the temperature variation but the change in visibility is negligible. The visibility variation for these two different temperatures is 0.02 corresponding to a refractive index variation of 0.007. Figure 6(b) presents the FFT of the two spectral responses (24°C and 65°C, respectively). The difference is negligible. For higher temperature, a minor change of the FFT amplitude is noticeable.

3 CONCLUSIONS

This paper presents an alternative solution for an optical refractometer based on a Fabry-Pérot tip sensor formed by a suspended core between two single mode fibres. To our knowledge, it is the first time that a suspended core fibre is used as a Fabry-Pérot refractive index sensor. With this configuration it was possible to have a referencing cavity (the suspended core fibre) and a sensing cavity (the suspended core in conjunction with the section of SMF 28). The advantages of using a suspended core fibre in the Fabry-Pérot cavity are low temperature sensitivity and simple fibre to fibre integration. A FFT technique was used to characterize the spectral response in the spatial frequency domain being able to achieve a fast Fabry-Pérot interrogation process with higher sensitivity when compared to the direct analysis of the spectral response visibility. The temperature dependence of the refractometer was also analysed and we can conclude that for small temperature variation the refractometer is insensitive to temperature. For high temperature change and due to the associated cavity length change, it is possible to discriminate temperature and refractive index using the spatial frequency and amplitude peak change independent variables.

ACKNOWLEDGEMENTS

This work was supported by the COST 299 – Optical Fibres for New Challenges Facing the Information Society.

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