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Sugar concentration sensor based on a micro Fabry-Perot interferometer

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Abstract

In this work a fiber optic sensor based on a micro Fabry-Perot interferometer (MFPI) for measuring sugar concentration in distilled water is presented. Here the spectral fringes contrast of the MFPI decreases when the refractive index value that surrounds it increases. As each sugar solution has a specific refractive index value, it was possible to relate the sugar concentration of aqueous solutions by measuring the power reflected of one MFPI spectral fringe. Moreover the sensor response to refractive index changes is modelled by using the characteristic matrix method. Finally this sensing arrangement for measuring sugar concentrations achieved a sensitivity of -0.0123 dBm/(gr/100ml) for the measurement range from 0 to 30.88 gr/100 ml at 1538.27 nm wavelength.

Fabry-Perot Interferometer, Sugar Concentration, Refractive Index

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Introduction

Humans have been consuming sugar for many centuries. This product is one of the main ingredients to give sweetness to foods and beverages (Yusmawati et al., 2007). Therefore there are many producers of sugar and products that contain it. The production of sugar is accomplished by a variety of processes in the plants, making indispensable the development of efficient measurement techniques for the improvement of the process control and to preserve the quality of final products. Some traditional methods to measure sugar content are based on refractive index measurement of the solution. These methods are mainly based on a bulky prisms system (Dorn & Wolf, 1970). In recent years new techniques, based on fiber optic sensor to measure refractive index, have been developed.

These fiber sensors offer the advantages such a as immunity to electromagnetic interference, small size, capability of in-situ, and real time applications. Recently, a variety of fiber optic sensor to measure solute concentration of aqueous solutions have been reported, some of these sensors are based on: long period gratings (Chong et al., 2006; Jorge et al., 2012), modulated path optical fiber (Marzuki, Wulan & Riatun, 2016), Fresnel reflection from the tip of a fiber (Binu et al., 2009; Chang-Bong, 2003; Fujiwara, Ono, Manfrim, Santos & Suzuki, 2011), and a fiber removed portion (Guzman-Sepulveda et al., 2013; Jayanth Kumar et al., 2006).

In this work a sugar concentration sensing setup based on a micro Fabry-Perot interferometer is presented. Here the sensor head is a MFPI that is in the tip of a single mode fiber (SMF). The MFPI is a micro bubble fabricated with a segment of hollow core photonic crystal fiber.

Its reflected interference pattern can be modified when solution refractive index that surrounds it changes. These refractive index values can be obtained by changing sugar concentration in water distilled. In this sense the fringes contrast of the MFPI reflected pattern decreases when sugar concentration increases. Therefore it was possible to calculate sugar concentration of aqueous solutions by measuring the reflected power of the spectral fringes. Experimental sugar concentrations measurements within the range from 0 to 30.88 gr/100 ml are provided. Finally the sensor response to refractive index changes is modelled by using the characteristic matrix method.

Methodology

The proposed setup for measuring sugar concentration is shown in Figure 1. Here, the light of a pigtailed diode laser emitting at 980 nm, delivering a maximum output power of 200 mW, was coupled to a wavelength division multiplexer to pump an erbium doped fiber (Newport F-EDF-T3) of 3.4 m length.

Afterwards, the luminescence generated by the EDF travels toward the FPI through the circulator from the port 1 to the port 2. Finally, the reflected interference spectrum of the FPI was monitored at the port 3 of the circulator by using an optical spectrum analyser (OSA, Yokogawa AQ6370C) with a resolution of 0.02 nm.

In order to measure sugar concentration changes, the FPI was placed into a cuvette which was filled with different sugar solutions. In this arrangement the sensor head is the intrinsic MFPI which is based on an air microcavity. This was fabricated by splicing a segment of hollow core photonic crystal fiber (HC-1064-19 Cells Fiber Crystal) to a standard SMF.

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Here to splice both fibers a conventional arc fusion splicer (Fitel-S175) was used and the fabrication process described in detail by (Jauregui-Vazquez et al., 2013) was followed. In this process after fibres get spliced multiple electric discharges are applied in order to cleave the photonic crystal fiber. After this step an air microcavity (MFPI) at the tip of the SMF is obtained (Figure 2). The sensor head is a MFPI which is considered like a structure of two plane and parallel plates. The first plate is the microcavity with length d_1 with a refractive index n_1 and the second plate is the thin silica wall at the tip of the FPI with thickness d_2 with a refractive index n_2. The incident medium of the pile of plates is the SMF core, with a refractive index n_2, and the exit medium that will depend on the material surrounding the MFPI structure, has a refractive index n_e. For this structure as both plates have low reflectivity therefore only two main interference spectra will occur. The first interference spectrum will be generated within the air micro cavity while the second one will occur within the thin silica wall.

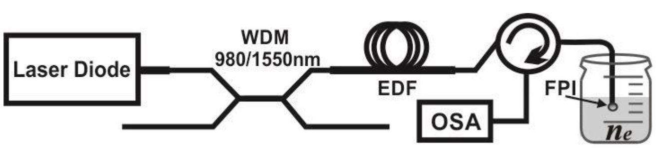

Figure 1. Sugar concentration sensing setup

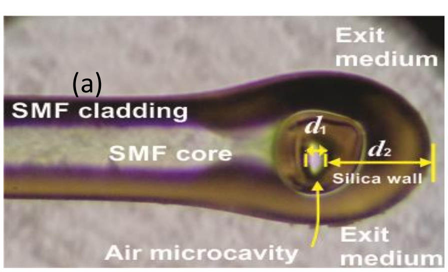

Figure 2. Picture of the fabricated MFPI.

Hence, as the overall MFPI is seen as a pile of plates therefore the final MFPI reflectivity fringe pattern can be calculated by using the characteristic matrix (Dorn & Wolf, 1970). Then the reflectance of this plate assembly can be obtained by using the following expression (Vargas-Rodriguez et al., 2015):

$$\begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} \cos\delta & -\frac{1}{n_1}\sin\delta \\ in_1\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} \cos\delta & -\frac{i}{n_2}\sin\delta \\ in_2\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} 1 \\ n_e \end{bmatrix} \quad (1)$$

$$\delta = \frac{2\pi n_{1,2} d_{1,2}}{\lambda} \quad (2)$$

where λ is the wavelength. Finally the reflectivity of the overall assembly is given by:

$$R_{FPI} = real\left(\frac{n_2A-B}{n_2A+B}\right)^2 + imag\left(\frac{n_2A-B}{n_2A+B}\right)^2 \quad (3)$$

In order to simulate our system response, we considered $d_1 = 12.7\ \mu m$, $d_2 = 110.9\ \mu m$, $n_1 = 1$, $n_2 = 1.44$. Simulated reflectivity spectra of the MFPI for three different n_e are shown in Fig. 3. Here, it can be appreciated that in this type of MFPI the contrast and the finesse of the spectral fringes occurring by multiple internal reflections within the second plate (the thin silica wall) will be modified (Fig. 3b).

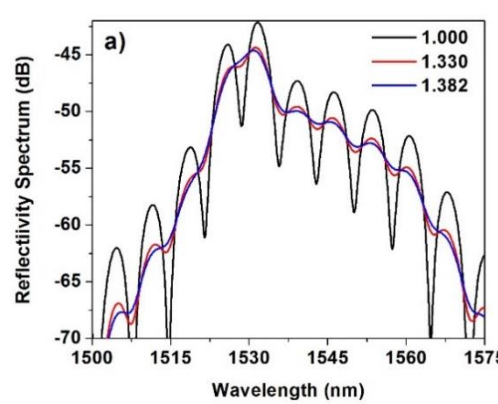

Figure 3. a) Simulated MFPI reflectivity spectra considering an exit medium with different refractive indexes. b) Detail of the FPI reflectivity spectra.

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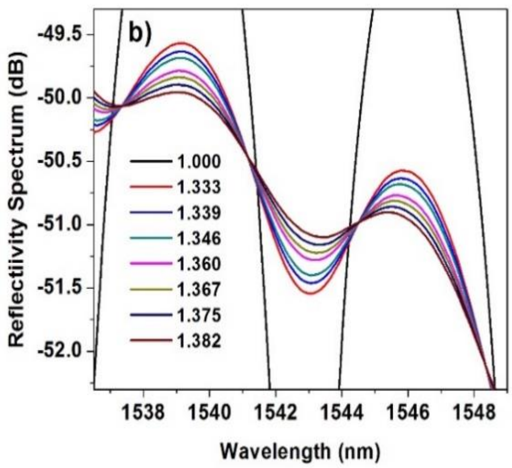
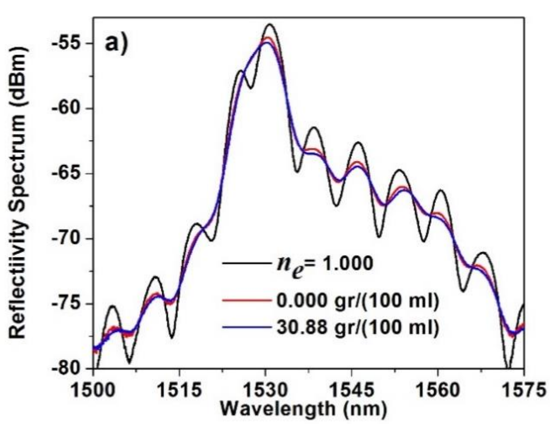


Sugar Concentration Sensor Response

The measured MFPI reflection profiles for two different sugar concentrations are shown in Figure 4a. Here the sugar concentrations were prepared using table sugar or granulated sugar and distilled water. The sugar concentrations that we used to characterize the sensor response were from 0 gr/100 ml to 30.88 0 gr/100 ml that correspond to the refractive indexes from 1.333 to 1.382 RIU respectively. In fig. 4b a detail of the spectral profiles for these sugar solutions are presented.

It can be observed that the contrast of the spectral fringe decreases when the refractive index of the sugar solution increases, related with the increase in sugar concentration. This behavior is predicted by the simulated results.



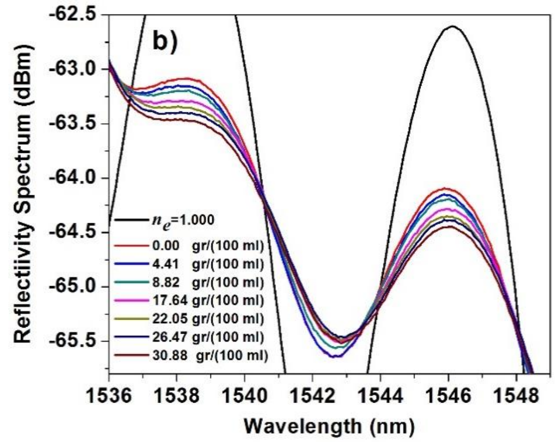


Figure 4. a) Measured reflected power spectra for different values of sugar concentrations and a b) Detail of the spectra.

As the contrast of the spectral fringes changes as the sugar concentration of the exit medium is varied, therefore it is possible to detect these changes by measuring the amount of reflected light at certain wavelength.

For instance, we select the maximum of one fringe, which in our case occur at $\lambda = 1538.27$ nm (Fig.4b). Moreover, the reflected energy, in dBm, as a function of the sugar concentration and the refractive index is presented in Figure 5. It can be noticed that the reflected light by the MFPI at $\lambda = 1538.27$ nm can be fitted very well with a linear function. The linearity has a correlation coefficient of 0.998.

Moreover, from these measurements it is possible to determine that the sensor has a sensitivity of -7.75 dBm/RIU or -0.0123 dBm (100 ml)/gr. Finally it is important to mention that measurements were taken directly with the OSA, however for practical reasons it must be replaced by a simple optical stage and low cost photodetectors (Vargas-Rodriguez et al., 2015).

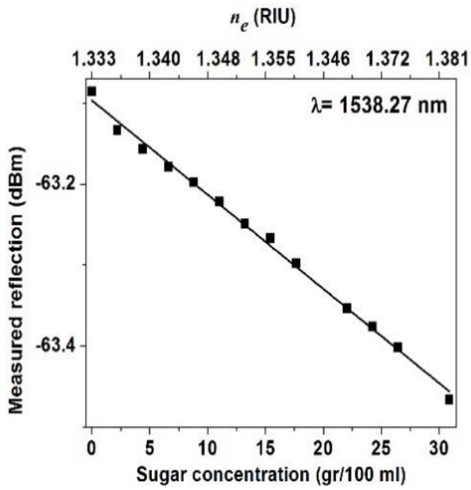


Figure 5. Measured reflected energy at $\lambda = 1538.27$ nm as a function of the sugar concentration and the exit medium refractive index

Conclusions

In this work a fiber optic sensor based on a micro Fabry-Perot interferometer (MFPI) for measuring sugar concentration in distilled water was presented. Here it was shown that the spectral fringes contrast of the MFPI decreased when the refractive index value that surrounds it increased.

As each sugar solution has a specific refractive index value, it was possible to relate the sugar concentration of aqueous solutions by measuring the power reflected of one MFPI spectral fringe. Moreover the sensor response to refractive index changes was modelled by using the characteristic matrix method.

Finally this sensing arrangement for measuring sugar concentrations achieved a sensitivity of -0.0123 dBm/(gr/100ml) for the measurement range from 0 to 30.88 gr/100 ml at 1538.27 nm wavelength

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