Dual parameter fiber optic sensor combining a Fabry-Perot and a Mach-Zehnder interferometer

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***Abstract*—A new concept for dual parameter fiber optic sensor has been developed and characterized, both in a two-fiber and single-fiber configuration. The liquid sensor measures ethanol concentration with a stimuli responsive hydrogel which constitutes a low finesse Fabry-Perot cavity, and refractive index with a Mach-Zehnder type fiber optic interferometer. The two-fiber configuration utilize a fiber optic 1310/1550 nm wavelength division multiplexer to separate the two parameters, while a versatile filtering algorithm extracts and separates the two parameters in the single-fiber configuration. No cross talk were observed for the measured parameters of free spectral range and refractive index for the two-fiber configurations, while for the single fiber configuration cross-talk were observed. The two configurations prove to be versatile dual parametric fiber optic sensor concepts for accurate detection of specific parameters, based on stimuli responsive hydrogels.**

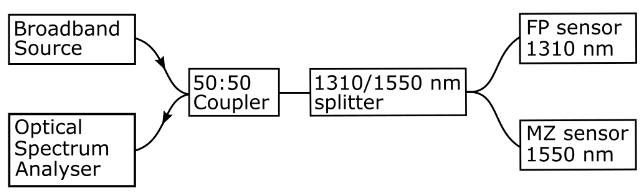
***Index Terms*—dual optical sensor, Fabry-Perot, Mach-Zehnder, interferometer**

I. Introduction

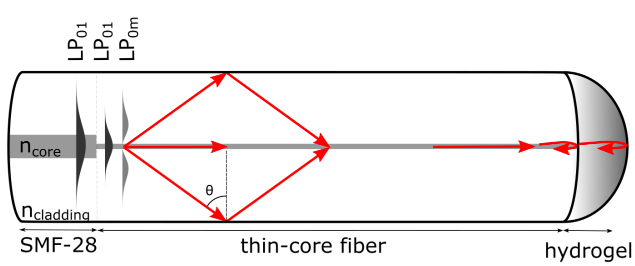
Many physical parameters depend on secondary parameters, for example pH and resistance are temperature dependent. Therefore, to accurately measure these parameters one often also need to measure the dependent value. At the same time one also want to have small sensors. To overcome these challenges we have developed an optical sensor to measure two parameters with two single mode fibers or on one single mode fiber. The two parameter concept is based on combining a Fabry-Perot interferometer (FPI) on the tip of the fiber [1], and a Mach-Zehnder interferometer (MZI) sensor that can measure refractive index on the side of the fiber [2], [3]. We have earlier reported a single strand, dual-parameter, fiber optic sensor [4], however the performance was severely limited due to cross-talk. In this contribution, we demonstrate improved performance by extending the read-out wavelength range and utilizing signal processing algorithms and filters. Free spectral range (FSR) is found for the FPI signal and further used to apply a fast Fourier transform based low pass filter on the MZI signal to evaluate the two signals separately. We compare the results to a two-fiber configuration where the sensor cross-talk is limited by physically separating the two sensors using a wavelength-division multiplexer (WDM) coupler.

For the proof-of-concept experiment, we utilize a stimuli responsive polymer in the FPI to sense ethanol concentration and the MZI to sense refractive index of glycerol/mQ-water solutions. The concept could be generalized using different stimuli responsive polymers in the FPI and as coating on the MZI fiber. Stimuli responsive polymers can measure many different physiological and biological parameters, thus making the sensor concept very versatile. The results in this paper are useful for combining sensing parameters of different stimuli responsive materials into a real-time fiber optic multi-parametric biosensor.

II. Experimental setup



(a)



(b)

Fig. 1. (a) Schematic of the experimental setup for the two-fiber dual sensor configuration. For the single-fiber dual sensor configuration, the splitter is omitted and the two sensors are combined as shown in (b) The thin core fiber acts as a MZI and the droplet on the fiber end (gray) is a FPI

Fig. 1a shows the measurement setup consisting of a broadband light source (FYLA SCT 500), a spectrometer (NIRQuest-512-1.7, Ocean Optics), a single mode 2x1-3 dB coupler (1550nm, Bredengen), and a 1310/1550 nm WDM (Thorlabs) with the two sensors. In the single-fiber configuration, the splitter is omitted and the two sensors are combined as shown in Fig. 1b.

On the end of the 3 dB coupler a 14 mm section of thin core fiber (SM450, Thorlabs) is spliced (Fitel fusion splicer, Furukawa Electric), which constitutes a Mach-Zehnder interferometer (MZI) with an intensity maximum around 1550nm. As this MZI is sensitive to the surrounding refractive index (RI), the maximum will shift in frequency. The hydrogel on the end of optical fiber (OF) in Fig. 1b acts as the Fabry-Perot interferometer (FPI). The hemispherical hydrogel was immobilized on fiber end-face as described in previous work by Tierney [1]. In this paper a pregel solution of 10 wt% of acrylamide (Sigma-Aldrich) and 2 mol% N,Nmethylenebisacrylamide (Sigma-Aldrich) monomers were polymerized into a hydrogel.

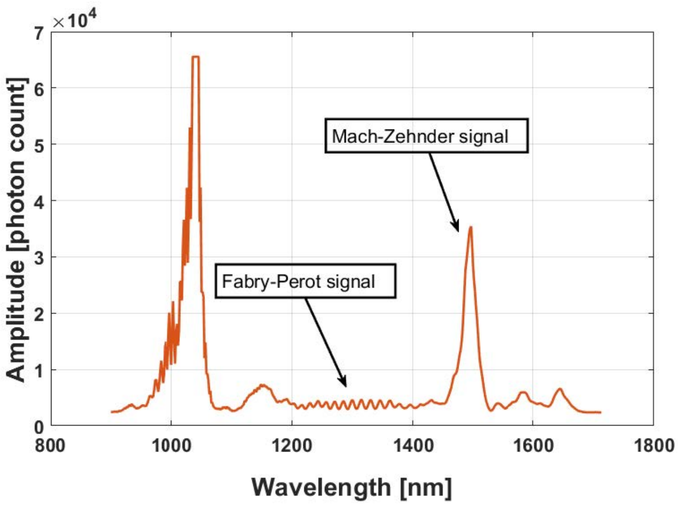


Fig. 2. Typical spectral output of dual point sensor shown in Fig. 1a. It is clearly seen that the two signals, from Fabry-Perot interferometer (around 1310 nm) and Mach-Zehnder interferometer maxima (around 1550 nm), does not interfere with each other

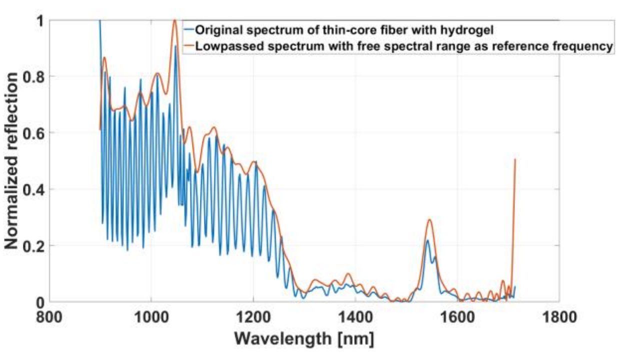
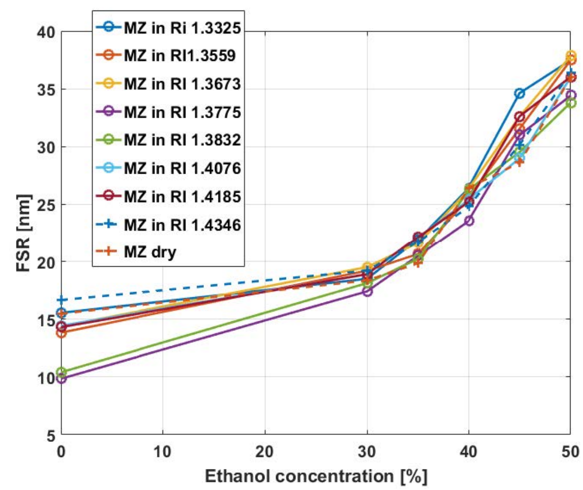


Fig. 3. Typical spectral output from single fiber dual sensor shown in Fig. 1b. The blue line is the original spectral output and the orange line shows the same signal when filtered with a low pass filter.

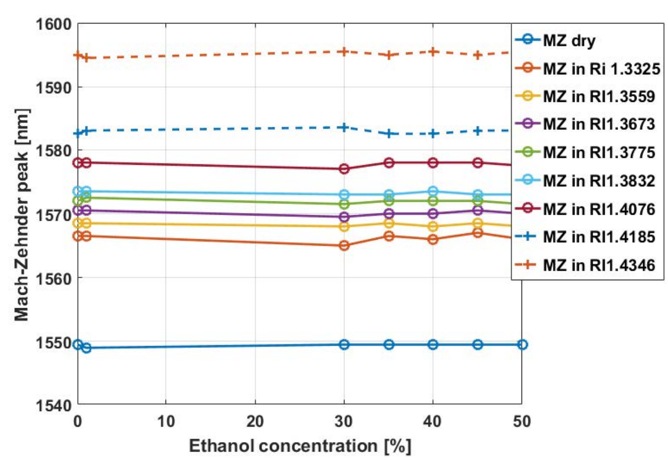
The hydrogel responds to specific chemical stimuli from the surrounding liquid environment and is monitored by measuring the free spectral range (FSR) or the phase of the sinusoid signal. For the OF system in Fig. 1a the FPI is measured in the 1310 nm range while MZI is measured in the 1550 nm range. The signals in a type of system like this, will add, but not interfere. The sensors can then be read out independently by selecting proper wavelength ranges, as indicated in Fig. 2. For an OF system as in Fig. 1b, the signals will interfere, but due to the large difference in FSR (Fig. 3) it is possible to find the FSR from the FPI signal to create a fast Fourier transform (FFT) based low-pass filter. This is used on the MZI signal to accurately determine its peak wavelength. In Fig. 3, the FPI is measured in 1100 nm range, while MZI is measured in the 1550 nm range.

III. Results

Both sensor configurations where characterized with regards to ethanol concentration and various RI solutions made from glycerol and mQ-water. The measured FSR (a) and the MZI peak (b) are shown as a function of ethanol concentration for different RI solutions for the two-fiber configuration, in Fig. 4.



(a)

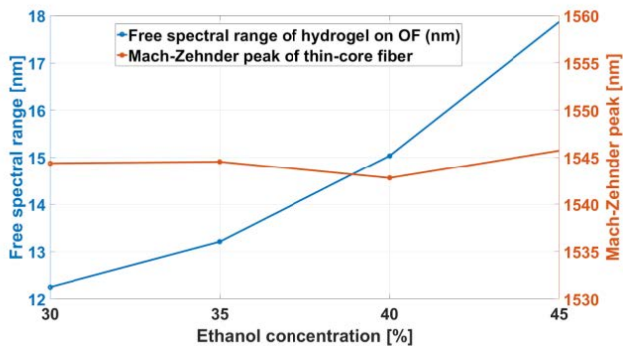


(b)

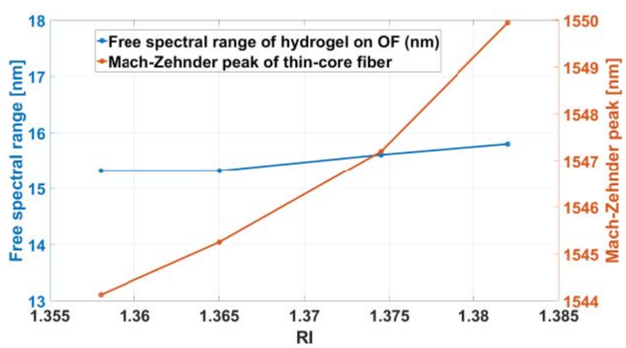
Fig. 4. (a) Free spectral range (a) and MZI minima as a function of Ethanol concentration (b) from the sensor system shown in Fig. 1, which shows the independency of the two sensors.

As expected, the FSR increases with higher ethanol concentrations, with little or no influence from RI changes. The MZI peak is also red shifting for increasing RI with little or no influence from changes in the ethanol concentration. The small cross-talk between the signals is minimized by using the WDM to detect FPI only in the 1310 nm range and MZI only in the 1550nm range. This dual point and dual parameter sensor proves to be useful for accurate multi-parameter sensing of stimuli responsive materials with negligible or no mixing of the signals [2], [3].

The measured FSR and the MZI peak wavelength were measured as a function of RI and ethanol concentrations for the single-fiber configuration shown in Fig. 5.



(a)



(b)

Fig. 5. (a) Free spectral range (a) and MZI minima as a function of Ethanol concentration (b) from the sensor system shown in Fig. 1, which shows the independency of the two sensors.

The FSR increases for increasing ethanol concentrations and MZI peak is red-shifting for increase in RI. Due to the amplitude mixing of the FPI and MZI signal, it was expected to have some cross-talk. The FSR measured as a function of RI increases slightly from 15.2 to 15.5 nm, which is probably caused by hydrogel shrinking due to the increase of glycerol concentration. The MZI peak measured as a function of ethanol varies slightly between 1444 and 1446 nm. These variations are likely caused by a changed interference between the core and cladding modes in the thin-core fiber due to the change in optical length of the hydrogel cavity.

IV. Conclusion

A single and dual point multi-parameter fiber optic sensor have been evaluated. The concept was demonstrated by simultaneous measurement of volumetric size of hydrogel stimulated by ethanol concentrations and refractive index of different glycerol, ethanol and mQ-water solutions. A FPI based on a hydrogel on fiber end-face was combined with a MZI that sense the RI on the fiber side-face. The dual point sensor concept proved to measure FSR and peak of MZI with negligible or no cross-talk due to the WDM separating and combining the light frequencies from the FPI and MZI. The single point sensor measured FSR and peak of MZI with a small cross-talk, which is probably caused by hydrogel shrinking due to the increased glycerol concentration. The cross-talk between peak of MZI and FSR, is due to the changed interference of the core and cladding modes in the thin-core OF for the different optical lengths of the hydrogel. Despite the small cross-talk, the single-fiber configuration shows to be useful in applications where single point and multi-parameter sensing is required, e.g. in medical applications where the sensing of biomarkers often are performed intravenously. Furthermore, by applying other stimuli responsive materials on the side and on the end of the OF the sensor could be modified to sense other parameters. Future work include the development and characterization of a dual and single point parameter OF biosensor system for in vivo measurements of pH and glucose.

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