Combining interferometric sensors for dual parameter fiber optic chemical sensing

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Abstract: Long and short path length differences interferometric sensing modalities have been combined based on immobilizing hydrogel on thin-core optical fiber end face. Dual parameter sensing of hydrogel swelling and refractive index was demonstrated. © 2018 The Author(s)
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1. Introduction

Miniaturization of optical fiber (OF) sensors is an important objective for biochemical monitoring as small sizes means fast diffusion times and sensor response [1]. In addition to sensor miniaturization, some applications requires the sensor to monitor several parameters in a single point. Multiparameter sensing can be achieved with multiple (OF) sensor elements, but its total size might not be acceptable in point-of-care settings. To satisfy the requirements for biochemical monitoring in point-of-care settings we have explored a concept of combining high and low frequency (in the wavelength domain) interferometric signals from the reflection of a stimuli-responsive hydrogel immobilized on the end face of a thin-core OF. The hydrogel on OF end face represents a Fabry-Perot (FP) interferometer [2] whereas the thin-core spliced on a single mode OF represents a Mach-Zehnder (MZ) interferometer [3, 4], as shown in Fig. 1. This OF sensor architecture have the potential to be combined with stimuli-responsive polymers to monitor pH and glucose in patients in intensive care units [5].
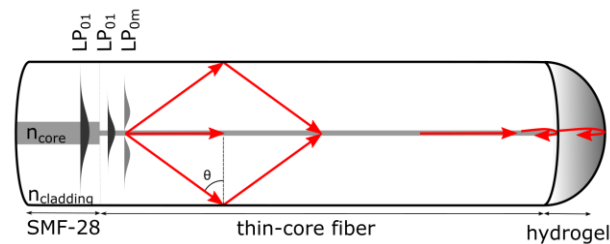

Fig. 1. Illustration of the MZFP sensor. The hydrogel represents the FP cavity and the thin-core represents the MZ interferometer.

The reflection spectrum is measured in the 1550 nm range for both signals. Since the FP signal is a high frequency signal and the MZ is a low frequency signal, it is possible to separate them by using Fourier transform based filtering algorithms. By extracting the high frequency FP signal, the optical length changes in the hydrogel sensor can be detected by measuring changes in the free spectral range (FSR) or the phase changes in the reflection spectrum. By extracting the low frequency MZ signal, the changes in refractive index (RI) on the cladding interface of the thin-core can be detected by measuring the changes in the MZ peak position in the reflection spectrum.

   In this proof-of-concept experiment we evaluate the quality of the extracted FP and MZ signals as well as the cross-talk between them for different hydrogel swelling equilibriums and RI changes. The hydrogel deswelling is controlled with increasing ethanol concentrations and the RI is controlled with glycerol in ethanol solutions. Some cross talk is expected to occur since the two signals are mixed in the same wavelength range. However, by designing the thin-core so its interferometric frequency signal is much lower than the interferometric frequency signal from the hydrogel on OF end face, this cross talk can be suppressed. The results in this paper are useful for developing OF design for obtaining dual parametric monitoring of two different stimuli-responsive hydrogels or polymers.

2. Materials and Methods

The OF setup in Fig. 2 is composed of the following components; broadband source (S5FC1005S, 1550 nm, 50 nm bandwidth, Thorlabs), spectrometer (NIRQuest-512-1.7, Ocean Optics), 50:50 coupler single mode (50/50, 84075633, 1550 nm, Bredengen). The end of the 50:50 coupler is spliced (Fitel fusion splicer, Furukawa

Electric) with a 14.5 mm thin-core (SM450, Thorlabs) which represents the MZ interferometer with intensity maximum around 1550 nm. The semi-spherical hydrogel was immobilized on the OF end face as described in earlier work [6]. In this paper the hydrogel is composed of 10 wt% acrylamide (Sigma-Aldrich) and 2 mol% N,Nmethylenebisacrylamide (Sigma-Aldrich).
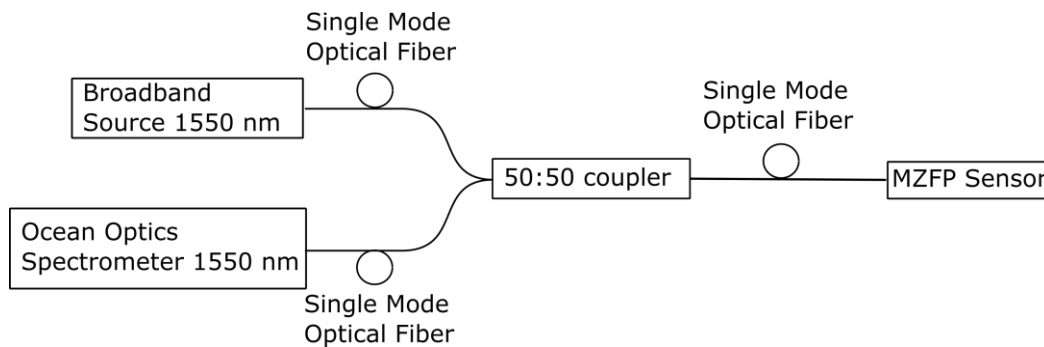

Fig. 2. Overview over the components used in the OF setup

The total MZFP signal was subtracted by the low frequency MZ signal (found by using Fourier transform based algorithms) to extract the FP signal. The optical length changes of the different hydrogel swelling equilibriums were computed by using an autocorrelation function to estimate the free spectral range (FSR) as performed in [7]. The total MZFP signal was filtered for the high frequency FP signal by using the estimated FSR as a reference frequency in the Fourier transform algorithms. The MZ peak position was estimated from this lowpassed filtered signal. Ethanol solutions were prepared by diluting ethanol in mQ-water and the RI solutions were prepared by diluting glycerol in 30% ethanol and mQ water solutions. The hydrogel swelling and RI were measured for two sampled series with mean and standard deviation from four sampled FSR or MZ peak positions.

3. Results and Discussion

Fig. 3 shows the total signal and the processed signals from the reflection of the MZFP sensor. The reflection from the MZFP sensor have a high frequency signal originating from the FP cavity on top of a low frequency
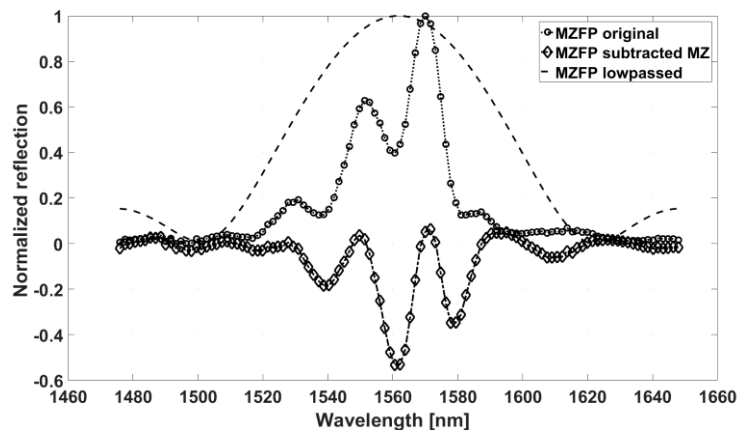

Fig. 3. Signal prossessing from the reflection spectrum of the MZFP

signal originating from the MZ interferometer. By using Fourier transform based filtering algorithms, the two signals can be separated. The fringes for the MZFP subtracted the MZ represents the signal from the FP cavity. The FP signal has a sufficient visibility for computing the optical length changes by detecting FSR, or phase changes. The lowpassed MZFP represents the MZ interferometer signal. The MZ signal is wider than the original MZFP signal. The quality of the MZ signal can be further improved by optimizing the thin core geometry and optimizing the filtering algorithms.

Fig. 4 shows the FSR and MZ peak position response for hydrogel deswelling controlled with increasing ethanol concentrations and RI controlled with increasing wt% of glycerol in 30% ethanol concentration. In Fig. 4a the FSR is increasing monotonically for hydrogel deswelling. This demonstrates that the interferometric signal from the FP cavity can be extracted from the total MZFP signal and used for detecting the optical length

changes. In Fig. 4b the FSR for increasing RI varies with ± 2 nm, which are likely due to the glycerol solutions that is changing the hydrogel swelling equilibriums. The small FSR changes for increasing RI shows that the optical length changes in FP cavity can be measured despite the large changes in the MZ peak positions. For Fig. 4c the MZ peak position for hydrogel deswelling varies with ± 1 nm, which is most likely due to the changed interference between the core and cladding modes in the thin-core fiber for different optical length
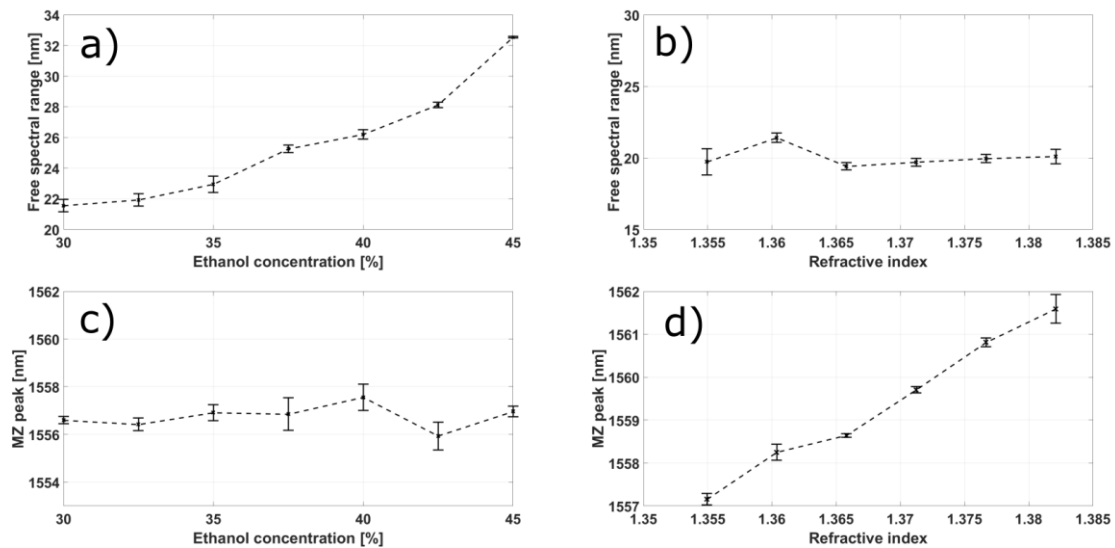

Fig. 4. **(a)** Computed FSR from optical length changes in the FP cavity for hydrogel deswelling for increasing ethanol concentrations; **(b)** Computed FSR from optical length changes in the FP cavity for increasing RI controlled with glycerol in 30% ethanol solutions; **(c)** Computed MZ peak position for hydrogel deswelling for increasing ethanol concentrations; **(d)** Computed MZ peak position for increasing RI controlled with glycerol in 30% ethanol solutions. The hydrogel swelling and RI were sampled for two series with mean and standard deviation from four sampled FSR and MZ peak positions. The error bar represent the standard deviation and the center of the error bar represents the mean.

changes in the FP cavity. However, the small variations in the MZ peak positions shows that the MZ signal and peak positions can be measured despite the large optical length changes. In Fig. 4d the MZ peak positions are increasing monotonically for increasing RI. This demonstrates that the MZ signal can be extracted from the total MZFP signal and used for detecting RI changes on the side face of the thin-core.

3. Conclusion

A single point multiparameter fiber optic sensor has been demonstrated based on using interferometric signals from the reflection of a hydrogel immobilized on the end face of a thin-core fiber spliced to a standard single mode OF in the 1550 nm range. The hydrogel represents a FP cavity with a high frequency interferometric signal, whereas the thin-core represents a MZ interferometer with a low frequency interferometric signal. The FP signal is used for detecting changes in the hydrogel swelling equilibriums and the MZ is used for detecting RI changes on the thin-core cladding interface. By controlling the hydrogel swelling with ethanol concentration and the RI with glycerol solutions, we showed that both hydrogel swelling and RI changes could be monitored with FP and MZ signals, respectively. The cross-talk between the signals was shown to be small. The FSR for RI was varying with ± 2 nm and the MZ peak position for hydrogel swelling was varying with ± 1 nm. By applying stimuli-responsive (pH or glucose) polymers on the side face and the end face of the thin-core OF, it can be used in medical applications for sensing biomarkers. Further work will consist of assessing this OF system for simultaneous measurements of pH and glucose.

4. References

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