MZI based interrogation of a ring-resonator ultrasound sensor

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We demonstrate the interrogation of a ring resonator (RR) sensor for ultrasound using a fiber Mach-Zehnder interferometer. The RR sensor is promising device for medical ultrasound imaging, in particular for intravascular ultrasound imaging (IVUS). We identified the amplitude of the angular deflection Φ_0 on the circle arc periodically traced in the plane of the two orthogonal interrogator voltages as the main interrogator output. The procedure yields a well-defined relation between Φ_0 and the applied ultrasound pressure.

Introduction

In this paper, we interrogate ultrasound sensor based on a ring resonator (RR) located on a thin membrane. Ultrasound waves make the membrane vibrate and as a result induce a modulation of the optical resonance wavelength of the RR. The sensor is very promising for medical ultrasound imaging, in particular for intravascular ultrasound (IVUS) imaging, which is widely used to diagnose atherosclerosis in humans. Important advantages of our sensor for IVUS are the high sensitivity [1] and the possibility to integrate an array of RR sensors in a single chip, due to CMOS fabrication technology. Moreover, no electrical wires are used, making it compatible to Magnetic Resonance Imaging examination.

The interrogation is based on a fiber Mach-Zehnder interferometer (MZI). The procedure yields a well-defined relation between the sensor signal and the applied ultrasound pressure. The minimum pressure amplitude obtained was 2.3 Pa, which is lower than actually needed for IVUS.

Interrogation of the ring resonator sensor

The sensor consists in a silicon ring resonator (RR), coupled to two bus waveguides, and located on a silicon oxide membrane. The ring was fabricated in IMEC, via ePIXfab[2]. The ring shape is a racetrack and the length of the straight part is 30 µm, while the bending radius is 5.0 µm. The dimensions of the ring waveguide cross section are 220 nm × 400 nm, implying that the waveguide is singlemode at the wavelength of 1550 nm. For light coupling, we use grating couplers (GCs), which are connected to the ring pass and drop port. The GCs are polarization sensitive, implying that the modes coupled into and out of the waveguides and circulating the ring are TE polarized. The sensor's membrane was fabricated in Kavli Nanob Delft. The membrane diameter is 66 µm, which leads to a vibrational mode at 1.3 MHz. When this mode is excited by ultrasound waves, the RR is deformed, encoding the optical signal with the information of the ultrasound wave. In particular, modulation of the RR resonance wavelength is proportional to incident pressure.

The interrogation of the RR senor is performed using the fiber optical circuit shown in Fig. (1). Light from a broadband source is guided to the RR sensor input port, via a circulator, a fiber Bragg grating (FBG) and an EDFA set at gain of 24 dB. The width of the FBG reflection spectrum is such that a single resonance of the ring resonator at λ_r =1550.20 nm is selected. The light from the sensor is guided to the MZI, of which one arm has a variable length air gap, thus providing a variable optical path difference (OPD). Two different OPDs values were used to interrogate the RR sensor: 12.9 mm and 6.9 mm. The air gap is realized using two lenses as indicated in Fig.1. Each coupler output is connected to a combination of a photodetector and a transimpedance amplifier. The resulting output voltages V_i are sampled by a data acquisition system (max. sampling rate 120 MSa/s). The sensor is immersed in a water tank, placed 135 mm from a 1.0 MHz transducer. In this paper, the sensor is interrogated using continuous waves at the frequency f_0=1.3 MHz, sampled at the rate 30 MSa/s.

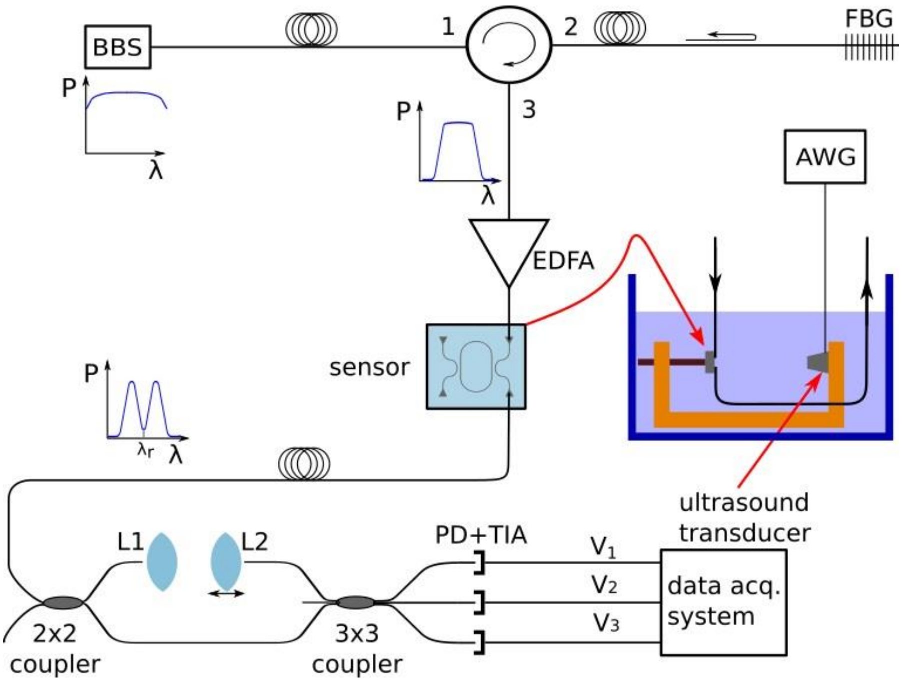

Figure 1: Schematic of the fiber interrogator, based on a Mach-Zehnder interferometer. BBS is the broad band source, FBG the fiber Bragg grating, EDFA the erbium doped amplifier and AWG the arbitrary waveform generator. The lenses L1 and L2 are part of the variable optical path length of one MZI arm, ranging from 4 to 13.5 mm. PD + TIA denotes combination of photodetector and transimpedance amplifier. V_1, V_2 and V_3 are the three output voltages used to calculate the orthogonal voltages V_x, and V_y and the angular deflection $\Phi(t)$.

Combining the 3 output voltages, we obtain the mutual orthogonal voltages V_x, V_y according to

$$V_x = 2V_1 - V_2 - V_3 = R\cos(\Phi(t) + \psi_e) + x_0 \qquad (1)$$
$$V_y = \sqrt{3}(V_3 - V_2) = R\sin(\Phi(t) + \psi_e) + y_0. \qquad (2)$$

The derivation of Eq. (1) and (2) is described in our theoretical model [3]. Here R is the circle radius, (x_0, y_0) are the center coordinates, and ψ_e is an arbitrary phase which depends on the environmental phase drift [4]. $\Phi(t)$ is the instantaneous angular deflection of the points (V_x(t), V_y(t)) on the arc of the circle and it is main outcome of the interrogator. It is proportional to the resonance wavelength modulation $\delta\lambda(t)$ and the ultrasound pressure $p(t)$ incident on the RR sensor.

For a reference ultrasound pressure of high enough amplitude, which produces a long enough arc of the circle, the radius R and the center (x_0, y_0) are determined by fitting a circle to the points (V_x(t), V_y(t)).The radius R is then used to obtain the circle center (x_0, y_0) for other amplitude pressures p_0 by minimizing the average squared deviations of the locus of points (V_x, V_y). Finally, we determine the instantaneous deflection according to

$$\Phi(t) = \text{atan2}\left(V_y - y_0, V_x - x_0\right), \qquad (3)$$

where atan2 is the four quadrant inverse tangent function. For a continuous ultrasound wave $p(t) = p_0 \sin(2\pi f_0 t)$ and $\Phi(t) = \Phi_0 \sin(2\pi f_0 t)$. The amplitude of the angular deflection Φ_0 equals the peak of the Fourier transform of $\Phi(t)$. The relation between Φ_0 and the amplitude of the resonance modulation δ_0 is given by

$$\delta_0 = \kappa \, \frac{\lambda_r^2 \, \Phi_0}{2\pi \, OPD}. \qquad (4)$$

Here OPD is the MZI optical path difference and κ is the correction factor. The origin of κ is detailed in our theoretical model [3] and experimentally determined using an independent calibration method. κ value is 2.40 (OPD = 12.9 mm) and 2.60 (OPD = 6.9 mm).

Experimental Results

Following the steps described in the previous section, we calculated the mutual orthogonal voltages V_x(t) and V_y(t) from the measured output voltages $V_i(t)$ (i = 1,2,3), according to Eq. (1) and Eq. (2). Figs 2(a)–(d) show the data points (V_x(t), V_y(t)) for the pressures amplitudes of 570 Pa and 2280 Pa and for both OPDs. The figures indicate that the larger is the incident pressure amplitude, the larger is the amplitude of the angular deflection Φ_0, as expected from the discussion in previous section.

The chosen reference pressure amplitude is 2280 Pa and the corresponding angular deflections in $V_x - V_y$ plane are shown in Figs. 2(c) and 2(d). The retrieved radii from the fit are R = 191±6 mV and R = 200±21 mV for OPD values of 12.9 and 6.9 mm, respectively. Using the retrieved radii, we obtained the angular deflection for all pressure amplitudes in the range 2.3 – 5750 Pa. Results are shown in Fig. 2(e). Fig 2(f) shows a zoom of Fig. 2(e) for the pressure range 2.3 – 30 Pa. The minimum pressure obtained is 2.3 Pa, much lower than the needed for IVUS. Figs. 2(e) and 2(f) also show straight lines through origin fitted to the data points. As can be seen, the scatter of the points around the fitted lines is small, confirming the linear relation between Φ_0 and p_0. The slopes of the lines, which correspond to the sensitivities of the system formed by the RR sensor and interrogator combined, are 0.30±0.02 (OPD = 12.9 mm) and 0.15±0.02 milliradian/Pa (OPD = 6.9 mm). A larger sensitivity is observed for OPD = 12.9 mm, in agreement with Eq. (4).

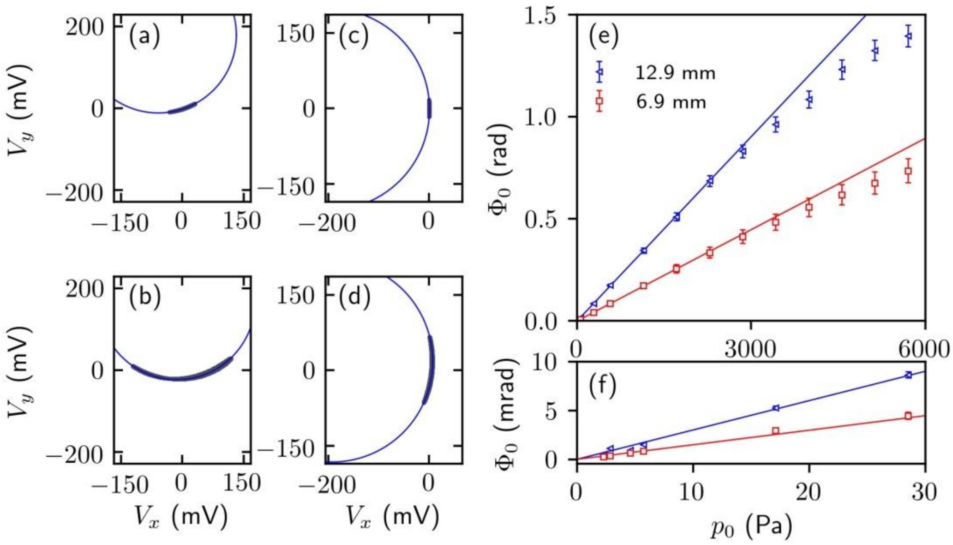

Figure 2: Main results of the interrogation of the sensor: (a)-(b) data points $(V_x(t), V_y(t))$ for OPD = 12.9 mm and fitted circle. (c)-(d) data points $(V_x(t), V_y(t))$ for OPD = 6.9 mm and fitted circle. The pressure amplitudes are 570 Pa for (a) and (c) and 2280 Pa for (b) and (d). (e) Amplitude of the angular deflection Φ_0 as a function of the pressure amplitude of 1.3 MHz ultrasound waves applied to the sensor. The lines are fitted straight lines through origin to the data points. (f) Zoom-in of (e) for points in the range 0-30 Pa.

Conclusion

We interrogated a silicon ring-resonator sensor for ultrasound using an interrogator based on a fiber Mach-Zehnder interferometer (MZI). We demonstrated the linear relations between Φ_0 and the pressure amplitude of continuous wave 1.3 MHz ultrasound applied to the sensor, for optical path differences (OPDs) of the MZI of 6.9 and 12.9 mm. The minimum detected pressure was as low as 2.3 Pa. The sensitivities are 0.30 and 0.15 milliradian/Pa, respectively.

This work on the fiber interrogator is an important step towards an integrated photonics interrogator, which is our next goal. An integrated photonics version can be designed for interrogating an array of integrated ultrasound sensors for IVUS by applying multiplexing using arrayed waveguide gratings.

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