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Enhancing the sensitivity of silicon photonic ultrasound sensors by optimizing the stiffness of polymer cladding

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Ultrasound is widely used in medical imaging, and photo-acoustics is an upcoming imaging modality for the diagnosis of diseases. Future applications require a large matrix of small, sensitive, and broadband ultrasound sensors. However, current high-end systems still use piezo-electric material to detect ultrasound, with limited sensitivity and bandwidth. Silicon photonic circuits can meet the requirements of size, bandwidth, and scalability when designed as ultrasound sensors. Namely, a silicon photonic waveguide deforms when the ultrasound pressure waves impinge on it, leading to a change in effective refractive index, n_e, due to geometrical and photo-elastic effects [1]. However, these effects are weak, which limits the intrinsic sensitivity of silicon photonic ultrasound sensors [2]. To significantly enhance sensitivity, silicon waveguides have been combined with acousto-mechanical structures, which achieved acoustomechanical-noise-limited sensing [3], but this is not compatible with standard photonic platforms. Besides that, recent demonstrations of waveguides coated with polymers also improved sensitivity of the silicon photonic ultrasound sensors significantly, but not sufficient to reach acoustomechnical-noise-limited sensing [4]. Here, we study the effect of mechanical and opto-mechanical properties of polymer claddings on the sensitivity of silicon photonic ultrasound sensors. Our aim is to enhance the sensitivity of these devices by implementing tailored polymer coatings. First, we model the refractive index sensitivity of these type of waveguides, i.e. the change in effective refractive index n_e due to the incident ultrasound plane-wave with a pressure P , and we find:

$$\frac{\partial n_e}{\partial P} = \frac{\partial n_e}{\partial n_c} \cdot \frac{\partial n_c}{\partial P} = -\frac{\partial n_e}{\partial n_c} \cdot \frac{1}{2} n_c^3 p_{12} \cdot \frac{(1-2v)(1+v)}{1-v} \frac{1}{E} \tag{1}$$

where n_c, p_{12}, E, and v are refractive index, elasto-optic coefficient, Young's modulus (stiffness), and Poisson's ratio of the cladding material, respectively. We assume the change in cladding index dominates sensitivity.

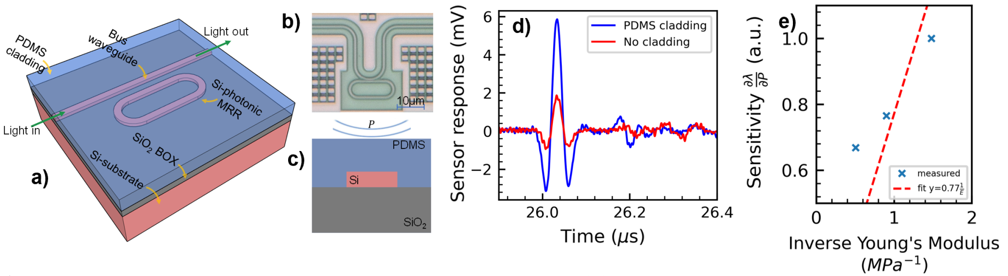

Fig. 1 a) 3D sketch, b) microscope image, and c) cross-sectional sketch of the PDMS coated silicon photonic ring-resonator. d) Recorded response of the silicon photonic ultrasound sensor to the incident ultrasound pulse with and without PDMS cladding (averaged 3000x). e) Resonance shift sensitivity for different stiffness of the cladding.

Second, we experimentally investigate the sensor sensitivity as a function of cladding stiffness. Silicon photonic chips with ring resonators were fabricated at IMEC's CMOS pilot line. As a simple addition to the CMOS fabrication, we mixed PDMS with distinct curing-agent-to-base-ratios and spin-coated them on the devices to prepare claddings with different stiffness. We independently measured Young's modulus with nanoindentation, and we obtained 1.98 MPa, 1.11 MPa, and 0.676 MPa, for PDMS mixing ratios of 1:10, 1:15, and 1:20, respectively. To characterize these sensors, we fired ultrasound pulses in water and recorded the sensor response (Fig. 1d). The ultrasound-induced photonic resonance shift was interrogated by placing a laser on the flank of the optical resonance and measuring intensity modulation [3]. Then the resonance shift sensitivity $(\partial\lambda_r/\partial P)$ was computed by normalizing the sensor sensitivity $(\partial I/\partial P = \partial I/\partial\lambda_r \cdot \partial\lambda_r/\partial P)$ to the photonic sensitivity, i.e. the measured slope of the transmission curve $(\partial I/\partial\lambda_r)$ at the flank wavelength. We demonstrate ultrasound sensing with enhanced sensitivity by optimizing cladding stiffness. However, the observed dependence is not inversely proportional (see Eq. (1) and Fig.1e, dashed line), which may be caused by several effects and requires further investigation.

In conclusion, this work contributes to the development of large bandwidth, high resolution, high sensitivity, and scalable silicon photonic ultrasound detectors with the ultimate aim to enable challenging photoacoustic imaging applications such as intra-vascular imaging or living mouse brain imaging.

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