Ring Resonator Based Ultrasound Detection in a Zero-Change Advanced CMOS-SOI Process

Panagiotis Zarkos, Olivia Hsu, and Vladimir Stojanović
Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA
panzarkos@berkeley.edu

Abstract: Optical ultrasound detection using microring resonators (MRRs) in a zero-change 45*nm* CMOS-SOI electronic-photonic platform with high intrinsic sensitivity of $39.6 fm/kPa$ and frequency response of 6MHz is reported. © 2019 The Author(s)

OCIS codes: (130.3120) Integrated optics devices; (110.7170) Ultrasound; (130.6010) Sensors;

1. Introduction

Optical MRR-based ultrasound detectors are a competitive alternative to conventional ultrasonic transducers employing piezoelectric (PMUTs) or capacitive micro-machined sensors (CMUTs) [1], [2]. Their photonic nature allows them to be combined with emerging optical ultrasonic imaging modalities such as photoacoustic tomography, while their compact size and low power consumption make them ideal for endoscopic applications such as intravascular imaging and transesophageal echocardiography. Additionally, these applications require real-time 3-D imaging, which calls for a 2-D array of sensing elements to perform receiver beamforming. The beamforming array would consist of multiple MRR rows simultaneously interrogated by a comb laser, with spacing of adjacent resonances tuned to match that of the interrogating comb. Co-integrating both the MRRs and thermal tuning control circuits in a commercially available monolithic electronic-photonic process paves the way for a compact, low-power, optical ultrasonic probe.

In this paper we experimentally demonstrate that MRRs implemented in a monolithic electronic-photonic platform in a zero-change 45nm CMOS-SOI process [3] can act as ultrasound detectors. It is necessary to characterize the intrinsic sensitivity and bandwidth of these devices to demonstrate advantage over existing ultrasound solutions. Understanding the deformation modalities of the MRRs in response to mechanical disturbances in this platform enables design of optimized MRR-based ultrasound detectors in the future.

2. Principle of Operation and Intrinsic Sensitivity

The MRR-based sensor exhibits pressure-induced shifts of the resonant wavelength. As ultrasonic pressure waves impinge upon the chip, three physical phenomena simultaneously affect the ring resonance: waveguide deformation (Fig. 1a bottom inset), the opto-elastic effect, and perimeter elongation (Fig. 1a middle inset). The waveguide deformation leads to a less confined mode, which reduces the refractive index, causing a blue-shift of the resonance. The opto-elastic effect of silicon and elongation of the ring perimeter both red-shift the MRR resonance.

The bandwidth of the waveguide deformation and the opto-elastic effect can be evaluated by integrating the net stress distribution in the waveguide, as shown in [4]. Using this model with material properties relevant to our technology, we obtain the frequency response shown in Fig. 1b. The bandwidth increases dramatically as the waveguide height shrinks, indicating the advantage of the 45nm technology node with waveguide height of ≈ 80nm, compared to 220nm in other SOI processes [2], or the 1.4μm used in [1]. Given the small values of the opto-elastic coefficients of silicon, the induced photo-elastic shift is negligible compared to that caused by waveguide deformation.

The frequency response of ring elongation is obtained through FEM simulations, where the chip is treated as a rectangular membrane clamped on each side (with epoxy) and excited by a very broadband pressure wave (Blackman pulse, 80MHz center frequency). The OnScale FEM simulation results in Fig. 1c illustrate the narrowband

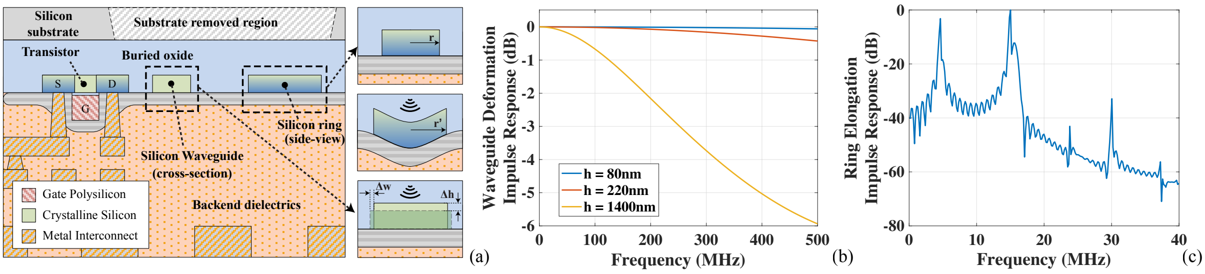

Fig. 1: (a) Zero-change 45nm CMOS-SOI process cross-section with insets showing the effect of a pressure wave causing ring elongation in side-view (top and middle), and waveguide deformation in cross-section (bottom), (b) Theoretical impulse response of waveguide deformation (normalized) (c) Simulated FEM impulse response of ring elongation (normalized)

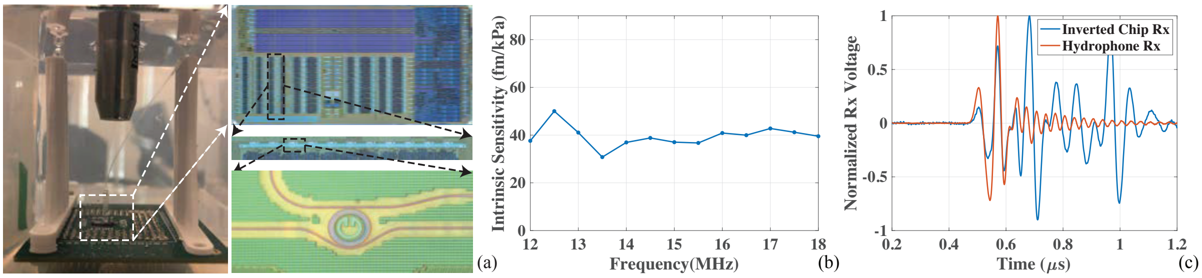

Fig. 2: (a) Part of the experimental setup showing the CMOS-SOI photonic chip and ultrasound transducer with insets presenting the die photo (top) and zoom-ins into the ring row tested (middle) as well as a single resonator disk (bottom), (b) Frequency sweep of the chip response, (c) Received time-domain signals of hydrophone and chip (inverted)

nature (around 100kHz) of the mechanical resonances, in agreement with [2]. After exciting the exact resonant modes in Fig. 1c in simulation, we saw that the effect of ring elongation is also not as significant as the effect of waveguide deformation, a result which is validated experimentally as well.

In addition to a broad frequency response, the devices in this monolithic platform need sufficient sensitivity to detect low pressure signals generated by the photoacoustic effect. The sensitivity of the ultrasound detector can be broken down as, $S = \frac{\partial V_{\text{out}}}{\partial P_{\text{app}}} = P_{\text{opt}} \frac{\partial T}{\partial \lambda_{\text{res}}} \frac{\partial \lambda_{\text{res}}}{\partial P_{\text{app}}} R_{\text{PD}} G_{\text{TIA}}$, where P_{opt} is the input optical power, T the normalized optical transmission, λ_{res} the resonant wavelength, R_{PD} and G_{TIA} the photodetector responsivity and transimpedance amplifier gain respectively, and P_{app} the applied pressure on the sensor surface. Traditional ultrasound systems measure detection sensitivity in [mV/kPa], indicating pressure induced voltage at the sensor output. However, in optical ultrasound sensors, where two independent transduction steps (pressure to optical power and optical power to voltage) occur, this metric is not appropriate. Therefore, we define intrinsic sensitivity, $S_{int} = \frac{\partial \lambda_{\text{res}}}{\partial P_{\text{app}}}$, as the amount of resonant shift caused per unit of applied pressure to characterize the sensor. This metric is a function of technology parameters and thus sets a fundamental limit of detection for a given technology.

3. Experimental Results and Discussion

Part of the experimental setup used in this work is depicted in Fig. 2a. A piezoelectric transducer (Olympus A313S) with 15MHz center frequency generates ultrasound, and its response is characterized using a commercial hydrophone (Onda HGL-1000). The chip is placed the same distance away from the transducer as the hydrophone, shown in Fig. 2a. Optical power from a CW laser at 1280nm is coupled into the chip through a polarization controller. The optical output of the chip is then driven into an external PD-TIA (ThorLabs, PDA10CF) and read out to an oscilloscope. The Q-factors of passive MRRs in this platform have been measured in the 100-200k range [5]. The Q-factor of the MRR modulators in the ring row available for this experiment is $\sim 10^4$. Large coupling losses (~7dB/coupler) in our setup required high input laser power, which in turn reduced the slope of the Lorentzian on the left of the resonance due to self heating. The measured optical transmission slope of 0.2μW/pm, average sensitivity of 12.6mV/MPa, and PD-TIA gain of 1.6V/mW indicate that the average intrinsic sensivity in this monolithic platform is 39.6fm/kPa. It is plotted in Fig. 2b over the 12-18MHz range.

In order to determine which resonant shift effect dominates, the laser is parked to the left of the resonance, and the transducer is excited using a high voltage pulser. Since the MRR is biased at the left of the resonance, a blue shift will reduce the output power and a red shift will increase it. Hence, if positive pressure induces blue shift, the chip's response will be inverted with respect to the hydrophone's (where positive pressure yields positive output voltage). This is indeed the case as shown in Fig. 2c, validating the earlier claim that waveguide deformation dictates the response. This is further supported by the frequency sweep of Fig. 2b, where we see a relatively flat response around 15MHz. If ring elongation was the dominant effect, then a much sharper response would be observed, as in our FEM simulations in Fig. 1c, and in [2]. While we are currently limited by the experimental setup, there is no fundamental limitation to our device not achieving similar bandwidth to [1] as per Fig. 1b.

We have demonstrated that ultrasound detection with high intrinsic sensitivity and bandwidth can be achieved using MRRs in an electronic-photonic monolithic 45nm CMOS-SOI process. Combined with inherently large Q-factors available in the platform, this paves the way towards the implementation of a high-sensitivity fully integrated optical ultrasound sensor, with co-integrated thermal controls, capable of 3-D real-time ultrasonic imaging.

References

1. C. Zhang *et al.*,“Ultra-broad Bandwidth Ultrasound Detector...” in *CLEO*: Sciense and Innovations, (OSA, 2014), p. SM2H.6.pdf.
2. S. Leinders, *et al.*, “A sensitive optical micro-machined ultrasound sensor (OMUS)...” Sci. Rep. **5**, 14328 (2015).
3. C. Sun *et al.*,“Single-chip microprocessor that communicates directly using light,” Nature **528**, 534-538 (2015).
4. P. Beard, *et al.*, “Transduction Mechanisms of the Fabry-Perot...” IEEE Trans. Ultrason., Ferroelect., Freq. Contr. **46**(6), 1575–1582 (1999).
5. J. S. Orcutt, *et al.*,“Open foundry platform for high-performance electronic-photonic...” Opt. Express **20**(11), 12222–12232 (2012).