Monolithically Integrated Electronic-Photonic Ultrasound Receiver Using Microring Resonator

Panagiotis Zarkos, Sidney Buchbinder, Christos Adamopoulos, Olivia Hsu, Sarika Madhvapathy, Jake Whinnery, Pavan Bhargava and Vladimir Stojanović

Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA

panzarkos@berkeley.edu

Abstract: The first optical ultrasound sensor with co-integrated read-out circuitry is presented. Based on a micro-ring resonator (MRR), it has a measured 7.3mV/kPa sensitivity, 480Pa minimum detectable pressure, operating at 80% fractional bandwidth around 5MHz. © 2021 The Author(s)

1. Introduction

Optical ultrasound receivers based on MRRs [1], [2] have recently gained popularity over traditional sensors based on piezoelectric (PMUTs) and capacitive micromachined transducers (CMUTs) in a variety of ultrasound imaging applications. Breaking the sensitivity-bandwidth tradeoff of PMUTs and CMUTs, they combine high bandwidth with competitive intrinsic sensitivity, ensuring great axial resolution and making them highly suitable for photoacoustic imaging. At the same time, their low-form factor and power consumption allows them to be densely packed in 2-D beamforming arrays performing real-time 3-D imaging that is particularly useful in endoscopic applications, such as transesophageal echocardiography, stenting, and intravascular imaging.

In this work, we present the first MRR-based ultrasound sensor with read-out and resonance tuning control circuitry monolithically integrated on the same chip. The use of a commercial process [3] enables mass, rapid production of a compact imaging system-on-chip. The sensor sensitivity and noise equivalent pressure (NEP) are measured at an 80% fractional bandwidth around 5MHz, and the packaging procedure is outlined.

2. Electronic-Photonic System-on-Chip Design

The designed Electronic-Photonic System-on-Chip (EPSoC) is depicted in Fig. 1a, with inset zoom-ins onto a single receiver site illustrating the tight co-integration of the CMOS circuits with the MRR. Three 4x8 ring arrays have been implemented in order to beamform 3-D imaging scans. In this sensing scheme, a SiGe MRR is used both as sensor and photodetector, with a measured responsivity of ~ 0.4A/W. To allow simultaneous interrogation of all 8 MRRs in a row by a comb laser, each ring has dedicated receive and thermal tuning circuits. These circuits include a tunable gain transimpedance amplifier (TIA) converting the MRR photo-current into a voltage as well as an analog to digital converter (ADC) digitizing the received data for post-processing and digital thermal tuning control logic, integrating $\sim 10^5$ transistors in a $220 \times 180\mu m^2$ area.

In order to validate the electronic-photonic sensor-receiver, the input wavelength of a tunable CW laser at 1300nm was swept over a 2nm range, while Lorentzian transfer functions were captured through the on-chip electronic read-out. The Lorentzians shown in Fig. 1b, correspond to the same ring at high, medium and low receiver gain, having maximum slopes of 23, 10.3, and 4.4 LSBs/pm, respectively. The heater control logic locks the ring at the location of maximum slope, (~ 300 LSBs), keeping it in the linear region of operation to amplify the small-signal MRR sensor response to ultrasound excitation.

Having on-chip tunable gain, we can accommodate a wide variety of signals, from photoacoustic (~ 100Pa) to conventional ultrasound (100kPa-10MPa) without saturating the output. Additionally, monolithic co-integration

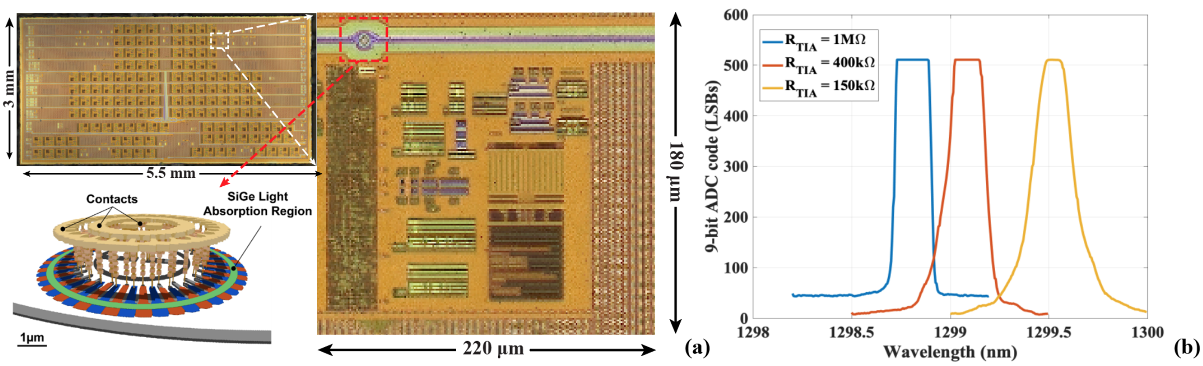

Fig. 1: (a) Chip-micrograph of the imaging EPSoC, implemented in a zero-change 45nm CMOS-SOI process, with inset zoom-ins on a single sensor-receiver and an MRR sensor-PD, (b) Measured Lorentzian transfer functions of the same MRR at different gain and heater settings. Heater settings: blue:OFF, red:15% of tuning range, yellow:30% of tuning range.

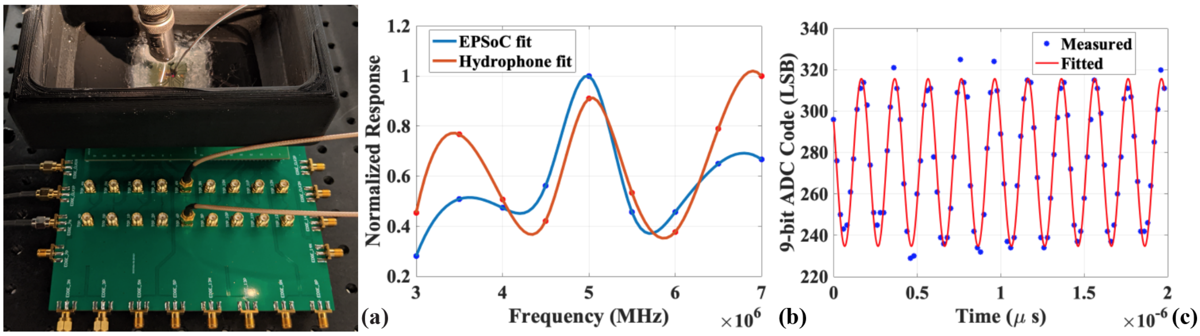

Fig. 2: (a) Part of the experimental setup showing the flip-chip packaged SOI CMOS EPSoC chip in the center of the water-tank with the fiber block attached onto it, and a piezoelectric transducer acting as a transmitter submerged over it, (b) Normalized amplitude vs frequency response of the EPSoC and a commercially available hydrophone (ONDA HGL-1000), (c) Received time-domain waveform corresponding to a 5MHz sinusoidal excitation.

of heaters comes with the benefit of very high tuning efficiency, which is measured to be 0.68pm/μW. This is an important system attribute considering 32 ring-resonators need to be simultaneously tuned.

3. Experimental Results and Discussion

To experimentally evaluate the sensor, a multi-step packaging procedure had to be performed. First, EPSoC dies were flip-chip attached onto an 8-layer PCB that fans-out digitized sensor response along with control and power signals. Subsequently, two etching steps were taken: a) silicon substrate XeF_2 etch that exposed the photonic sensor, and b) epoxy sidewall HNO_3 etch to allow attach of a 12-channel fiber block enabling simultaneous characterization of multiple sensing sites on the chip. Finally, to allow transducer immersion, a water-tank was 3D printed and glued on the edge of the board using silicone. A photo of the experimental setup is shown in Fig. 2a.

A piezoelectric transducer centered at 5MHz was used in the ultrasonic experiments. Fig. 2b shows the normalized frequency response of our sensor and a commercial hydrophone, placed the same distance away from the transducer. Both responses follow the same trend, while their ratio remains within 6dB in the 3-7MHz range corresponding to an 80% fractional bandwidth. Our MRR sensor has previously demonstrated a flat 40% fractional BW around 15MHz with good intrinsic sensitivity and can theoretically reach hundreds of MHz [4].

A time-domain response of our sensor at the maximum gain setting without any heating applied is plotted in Fig. 2c. It corresponds to a sinusoidal pressure excitation of 5MHz and a peak-peak amplitude of 12.1kPa. The unfitted measured waveform has a signal to noise and distortion ratio of 31dB and a fitted amplitude of 75 LSB codes. With the full scale of the 9-bit ADC corresponding to 0.6V we estimate the sensitivity of our sensor-receiver chain to be $S = \frac{600\text{mV}}{512} \cdot 75 \cdot \frac{1}{12.1\text{kPa}} = 7.3\text{mV/kPa}$, comparable to the sensitivity of commercially available hydrophones.

To theoretically measure the NEP of our sensor, we parked the laser at the resonance flank and recorded the digital output of the chip without any ultrasonic excitation. We found that the noise amplitude is 15 LSB codes without any averaging, while it drops down to 5 LSBs and 3 LSBs when 64 and 128 samples moving averages are used respectively. The ADC sampling rate was 50MHz, but can go up to 500MHz limited only by the on-chip 64-1 serialization. Defining as our NEP the point where SNR=1, and having experimentally verified the linearity of our detector, we can extrapolate the noise equivalent pressure to be $\text{NEP} = \frac{12.1\text{kPA}}{75/15} = 2.4\text{kPA}$ with no averaging, and 807PA and 480Pa respectively with 64 and 128 sample averaging.

This NEP result is slightly inferior to state-of-the-art optical ultrasound works [1] that have reported $\sim$ 100Pa NEP over 300MHz bandwidth, and 2 orders of magnitude below the piezo state-of the-art performance that can go down to 10s of Pa integrated over 4MHz [5]. This gap can be bridged in our approach by using a dual ring scheme, where a higher-Q MRR without SiGe is used as a modulator to sense the ultrasound and the SiGe PD-MRR to receive the modulated signal. Such structures exist on the designed EPSoC and their characterization is pending. Increasing the optical input power can also boost the SNR, since the presented measurements were performed with only 200μW reaching the ring. We anticipate our optimized dual-ring approach noise limit to be on-par with the state-of-the-art optical approaches and come close to the limit of detection achieved by modern PMUTs, while having orders of magnitude higher BW.

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