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● *Technical Note*

A BROADBAND POLYVINYLIDENE DIFLUORIDE-BASED HYDROPHONE WITH INTEGRATED READOUT CIRCUIT FOR INTRAVASCULAR PHOTOACOUSTIC IMAGING

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Abstract—Intravascular photoacoustic (IVPA) imaging can visualize the coronary atherosclerotic plaque composition on the basis of the optical absorption contrast. Most of the photoacoustic (PA) energy of human coronary plaque lipids was found to lie in the frequency band between 2 and 15 MHz requiring a very broadband transducer, especially if a combination with intravascular ultrasound is desired. We have developed a broadband polyvinylidene difluoride (PVDF) transducer (0.6 × 0.6 mm, 52 μm thick) with integrated electronics to match the low capacitance of such a small polyvinylidene difluoride element (<5 pF/mm^2) with the high capacitive load of the long cable (∼100 pF/m). The new readout circuit provides an output voltage with a sensitivity of about 3.8 μV/Pa at 2.25 MHz. Its response is flat within 10 dB in the range 2 to 15 MHz. The root mean square (rms) output noise level is 259 μV over the entire bandwidth (1–20 MHz), resulting in a minimum detectable pressure of 30 Pa at 2.25 MHz.
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Key Words: **Photoacoustic, Broadband receiver, Polyvinylidene difluoride transducer, Integrated circuit, Hydrophone, Atherosclerosis.**

INTRODUCTION

Cardiovascular diseases are the number one cause of death worldwide, causing about one-third of the total mortality (World Health Organization 2015). Nearly half of these cardiac deaths are due to acute coronary syndromes. The majority of these fatal acute coronary syndromes are caused by rupture of vulnerable plaques and thrombosis (Buja and Willerson 1994; Libby 2002; Libby et al. 2010; Schaar et al. 2004). Among imaging modalities targeting vulnerable plaques, photoacoustic (PA) imaging (Beard 2011) has been found to be capable of detecting and locating lipid components in the vessel wall, a major risk factor for plaque rupture (Madder et al. 2013), with reasonably large imaging depth (Jansen et al. 2011; 2014; Wang et al. 2011; 2012; 2013). This imaging technique, which applies pulsed light excitation, benefits from the optical absorption properties of tissue composition as contrast. Moreover, it has been established that the frequency range of the PA signal is inversely proportional to the dimensions of absorbing structures (Diebold 2009; Khan and Diebold 1995; Xu et al. 2015). As PA signals can be weak, it is important to match the transducer sensitivity to the frequency band providing the highest signal strength for *in vivo* imaging. In an *ex vivo* setup, we have observed that more than 80% of the emitted PA energy of human coronary plaque lipids lies in the frequency range 2 to 15 MHz with pressures typically on the order of 50 to 200 Pa (Daeichin et al. 2015). These results are in an agreement with the size of intra-plaque lipid structures observed in histologic slices (structures on the order of 100 μm). Multimodal imaging with intravascular photoacoustic imaging (IVPA) and intravascular ultrasound (IVUS) (Mintz et al. 2001) makes it possible to locate

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the chemical information provided by IVPA in the arterial structure imaged by IVUS. The frequency band of conventional IVUS transducers used in PA imaging systems is >20 MHz. Therefore, there is an urgent need in the field of intravascular PA imaging for a broadband and sensitive receiver that captures PA signals in the frequency range around 5 MHz.

Although the lead zirconate titanate (PZT) ceramics used in conventional IVUS transducers have been found to have good sensitivity, they have insufficient bandwidth to also cover the IVPA application discussed here. On the other hand, piezoelectric polymers, such as polyvinylidene difluoride (PVDF), have low acoustical impedance that is better matched to tissue and have outstanding broadband receiving performance, even with a small sensing area. However, because of the very low electrical capacitance of small PVDF elements (<5 pF/mm^2) compared with the much higher capacitance of the connecting coaxial cable (~100 pF/m), a buffer amplifier is required.

To solve this problem, particularly for intravascular imaging applications, we have designed and fabricated a readout integrated circuit (IC) that is connected directly behind the PVDF element inside the catheter tip. The sensitivity and receive transfer function of a prototype PVDF element integrated with the proposed IC have been evaluated and compared with those of a commercially available needle hydrophone (SN1875, Precision Acoustics, Dorset, UK). We refer to our probe as a PVDF element with integrated circuit (PIC), and the commercial hydrophone, as CH throughout the article.

METHODS

A 52-μm-thick PVDF film (Measurement Specialties, Hampton, VA, USA) was cut in a square shape (0.6 × 0.6 mm) using a laser micromachining workstation (FemtoLAB, Workshop of Photonics, Vilnius, Lithuania). This PVDF element was then directly mounted on top of a custom-designed readout IC to construct the PIC. This IC was designed using a Butterworth–Van Dyke model for electrical simulation, the parameters of which were derived from a KLM model of the PVDF element. The readout IC, fabricated in a standard 0.18-μm CMOS (complementary metal oxide semiconductor) process, consists of a trans-impedance amplifier (TIA) and a source follower (SF), as illustrated in Figure 1. The TIA converts the current generated by the PVDF element to voltage with a trans-impedance gain determined by the feedback network, R_f and C_f. When referred to the input of the readout IC, the noise contributions from succeeding circuits and the cable can be reduced by increasing the trans-impedance gain. As such, the TIA also performs as a low-noise amplifier (LNA). The SF provides a low output impedance to match the 50-Ω characteristic impedance of the cable. Both circuit blocks are powered by an external bias current source *via* a single micro-coaxial cable, which also carries the signal current drawn by the SF. The bias current is divided between the TIA and the SF by means of an on-chip current mirror (M_2 and M_4) with a low-pass filter (R_p and C_p) that prevents the output signal from feeding back into the TIA. Thus, the output impedance of the readout IC can be approximated as

$$Z_O \approx \frac{1}{g_{m3}} + \frac{1}{g_{m4}} \quad (1)$$

where g_{m3} and g_{m4} are the trans-conductances of M_3 and M_4, respectively. As g_{m3} and g_{m4} are both functions of the bias current (Allen and Holberg 2002), the output impedance of the readout IC can be adjusted by tuning the external current source, I_{bias}. At the system side, the output signal can be distinguished as a voltage V_{OUT} with a high-pass filter (R_{load} and C_{ac}).

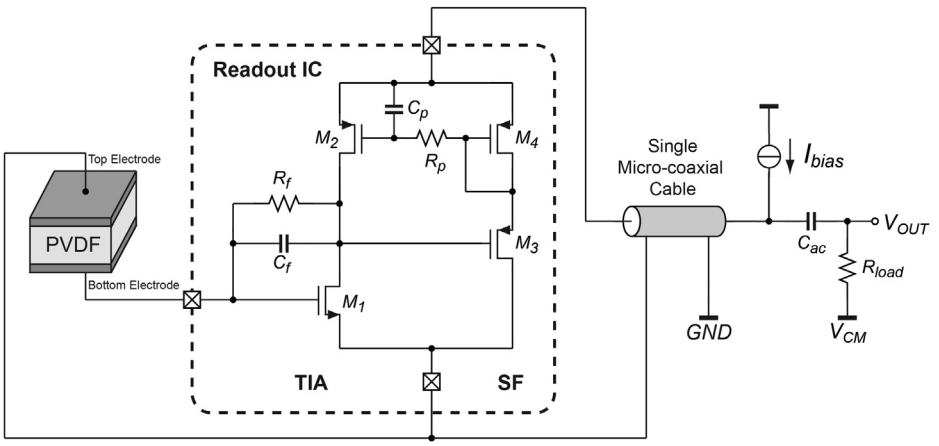

Fig. 1. Schematic of the proposed single-cable readout integrated circuit (IC).

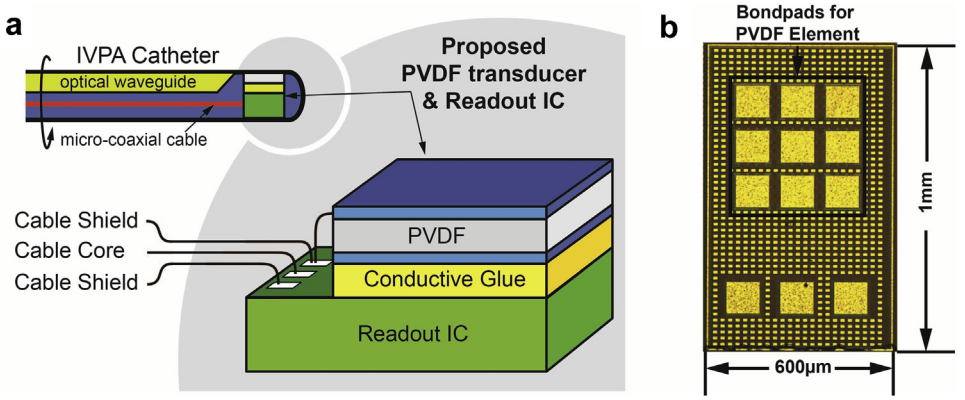

Fig. 2. (a) Architecture of the proposed IVPA catheter. (b) Schematic of the readout IC and its bond pads. PVDF = polyvinylidene difluoride; IVPA = intravascular photoacoustic; IC = integrated circuit.

The ground reference of the IC is provided by the shield of the 1-m-long micro-coaxial cable, which is also connected to the top electrode of the PVDF element. The bottom electrode of the PVDF element is directly glued to the input bond pads of the IC with electrically conductive adhesive (Emerson and Cuming, Westerlo, Belgium), as illustrated in Figure 2a.

Figure 2b is a schematic of the readout IC and its bond pads. The IC is designed as a rectangular die with dimensions 1 × 0.6 mm. While operating, it consumes 6 mA from the external current source.

The dynamic range of the PIC was measured using an unfocused single-element transducer with a center frequency of 2.25 MHz (PZT V306, Panametrics, Waltham, MA, USA, diameter = 12.7 mm) as an acoustical signal source. The pressure of the transmitted burst (5-cycle sinusoidal) was varied between 0.4 Pa and 40 kPa. The signal received by the PIC (positioned in the far field, 10 cm from the transducer) was first amplified using a low-noise amplifier (AU-3 A-0110-BNC, Miteq, Hauppauge, NY, USA) with 58-dB amplification gain and then filtered (20 MHz low pass) and digitized by an oscilloscope (TDS 3014 B, Tektronix, Beaverton, OR, USA). The recorded signals were analyzed offline using MATLAB (The MathWorks, Natick, MA, USA). The peak-to-peak voltage received by the PIC was measured for all transmitted acoustic pressures.

To measure the receiving transfer function, a broadband focused PVDF transducer (PVDF PA076, Precision Acoustics, Dorset, UK) was driven by a broadband ultrasonic pulse (2 ns wide and amplitude of 200 V, Avtech Electrosystems), and the generated pressure was probed at its focus (25 mm) using the CH with a known receiving transfer function (T_h) and using the PIC. The transfer function of the PIC was calculated using the method described by van Neer et al. (2007). Briefly, assuming similar diffraction correction functions for the PIC and CH (National Physical Laboratory 2013), the receive transfer function of the PIC (T_{PIC}) can be calculated as

$$T_{PIC} = \frac{F(V_{PIC})}{F(V_h)} \cdot T_h \qquad (2)$$

where $F(V_h)$ is the Fourier transformed voltage produced by a calibrated hydrophone, and $F(V_{PIC})$ is the Fourier transformed voltage produced by the PIC.

RESULTS

Table 1 is a performance summary of the readout IC. The peak-to-peak voltage received by the PIC is plotted against the peak-to-peak transmitted acoustic pressure in Figure 3a. The dynamic range (ratio of the maximum [30 kPa] to the minimum pressure [30 Pa]) is found to be around 60 dB. Acoustical results indicate that the PIC is sensitive enough to detect pressures as low as 30 Pa (peak to peak).

The receive transfer function of the PIC is depicted in Figure 3b. The frequency response of the PIC is flat within 10 dB in the frequency range 2 to 15 MHz. The amplification gain of the IC within this frequency range is flat within 3 dB. Similarly to the CH, the highest

Table 1. Performance summary of the single-wire readout integrated circuit

Technology	0.18 μm CMOS
Bias current	6 mA
Power consumption	13 mW
Operation bandwidth	1–20 MHz
Trans-impedance gain	100 dB Ω at 2 MHz
	80 dB Ω at 20 MHz
Integrated output noise	259 μV_{rms} at 1–20 MHz
Output impedance	~50 Ω
Total harmonic distortion	0.5% at 160 m_{Vpp} V_{out}

CMOS = complementary metal oxide semiconductor.

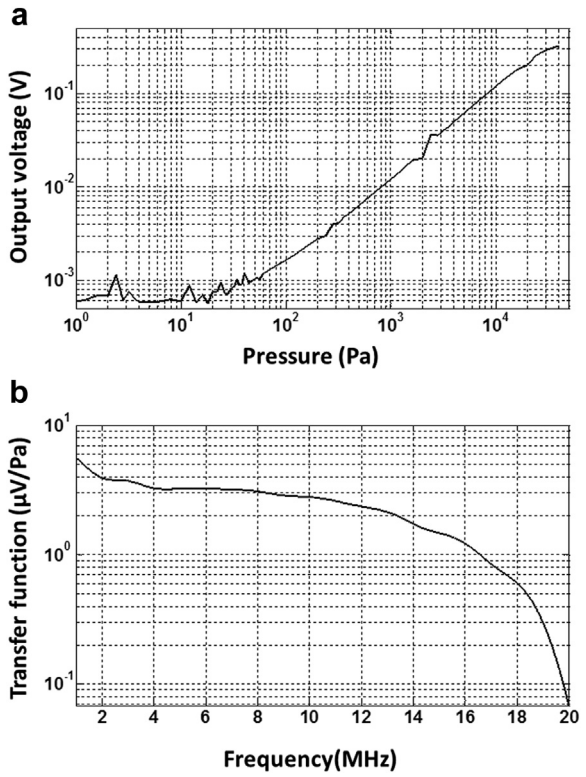

Fig. 3. (a) Measured output voltage (peak to peak) of the PIC as a function of the transmitted pressure (peak to peak), illustrating the dynamic range of the PIC; results were obtained using a 5-cycle sinusoidal pulse at 2.25 MHz. (b) Receive transfer function of the PIC, illustrating the sensitivity of the PIC. PIC = polyvinylidene difluoride element with integrated circuit.

sensitivity of our probe is at the lower part of the bandwidth (5.6 μV/Pa at 1 MHz), and at 2.25 MHz the sensitivity is 3.8 μV/Pa.

DISCUSSION AND CONCLUSIONS

We have developed a unique broadband (1–20 MHz) PVDF receiver with an integrated circuit (PIC) sensitive for acoustic pressures as low as 30 Pa to be incorporated inside an IVPA catheter with diameter of 1 mm. For optimal flexibility of the catheter, only one coaxial cable is used to power the IC and to read out the received signal from the IC.

Acoustical evaluation reveals that the receive transfer function of the PIC is similar to the that of the CH, which is flat within 10 dB in the frequency range 2 to15 MHz and drops more rapidly from 15 to 20 MHz. Moreover, integrated root mean square (rms) output noise voltage across the bandwidth of the PIC (1–20 MHz) was measured to be 259 μV. Such a low rms noise value indicates that pressures much lower than 30 Pa can be detected by limiting the receiving bandwidth. However, we reported the recorded peak-to-peak pressure (Fig. 3a) instead of the rms value because it is a more realistic measure for an imaging device. The improvement in the signal-to-noise ratio in comparison with the CH (National Physical Laboratory 2013) was very pronounced at higher transmit pressures at 2.25-MHz transmit frequency (18.4 dB at 1 kPa).

The maximum detected pressure at 2.25 MHz is about 30 kPa, resulting in a dynamic range of 60 dB. The maximum detectable pressure is limited by the saturation of the signal in the readout IC.

Ultimately, such a small and sensitive detector, which can be easily accommodated within a disposable catheter that will be capable of sensing acoustic pressures of a few pascals within the large frequency band 1 to 20 MHz, can significantly improve the sensitivity of IVPA imaging of intra-plaque lipids in humans and can dramatically decrease the required energy of the laser pulse.

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