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A novel dual-frequency imaging method for intravascular ultrasound applications

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ABSTRACT

Intravascular ultrasound (IVUS), which is able to delineate internal structures of vessel wall with fine spatial resolution, has greatly enriched the knowledge of coronary atherosclerosis. A novel dual-frequency imaging method is proposed in this paper for intravascular imaging applications. A probe combined two ultrasonic transducer elements with different center frequencies (36 MHz and 78 MHz) is designed and fabricated with PMN–PT single crystal material. It has the ability to balance both imaging depth and resolution, which are important imaging parameters for clinical test. A dual-channel imaging platform is also proposed for real-time imaging, and this platform has been proven to support programmable processing algorithms, flexible imaging control, and raw RF data acquisition for IVUS applications. Testing results show that the −6 dB axial and lateral imaging resolutions of low-frequency ultrasound are 78 and 132 μm, respectively. In terms of high-frequency ultrasound, axial and lateral resolutions are determined to be as high as 34 and 106 μm. *In vitro* intravascular imaging on healthy swine aorta is conducted to demonstrate the performance of the dual-frequency imaging method for IVUS applications.

1. Introduction

Although angiography is currently the golden standard for the assessment of coronary artery disease such as the degree of atherosclerotic stenosis, the structural information of vessel wall as well as the compositions of plaque, which are important parameters for assessment of the atherosclerotic disease burden, cannot be acquired [1]. Catheter based intravascular imaging methods, including intravascular ultrasound (IVUS), intravascular optical coherence tomography (IVOCT), etc., have been applied for the visualization, quantification, and characterization of atherosclerotic plaque as well as the guidance of intervention [2–5]. With these results, the knowledge of atherosclerosis has been greatly enriched by measuring the degree of stenosis, the structural information and the compositions of atherosclerotic plaque. Recently, research effort is being put to pursue higher resolution and stronger functionality of the imaging tool. For example, dual mode imaging method has been proposed for better visualization of the vulnerable plaque by combining optical imaging with IVUS. IVOCT is able to acquire the image with high resolution (∼10–20 μm), and IVUS has the ability to achieve large penetration (∼5–10 mm) [6,7]. However it makes the system more complicated and the cost of catheter and system will be increased. Similarly intravascular photoacoustics (IVPA) [8,9] has same issue with that. It is difficult to fabricate a catheter with ultrasonic transducer and optical device, and optical laser is still a luxury device in contrast with ultrasound facility.

Currently 20–40 MHz center frequency ultrasonic catheter is employed for clinical IVUS diagnosis. Theoretically, higher frequency ultrasound normally gains better resolution. For a typical transducer with bandwidth of 40% and a center frequency of 30 MHz, axial resolution of 62 μm is achieved. It can be improved to 31 μm and 19 μm when increasing the center frequency to 60 MHz and 100 MHz respectively [10]. High-frequency ultrasonic transducer with 82 MHz center frequency had been proposed and fabricated [11], and this type of transducer is shown to have great potential in providing superior resolution for clinical diagnosis. However the penetration depth has to be sacrificed with an increased ultrasound frequency [10].

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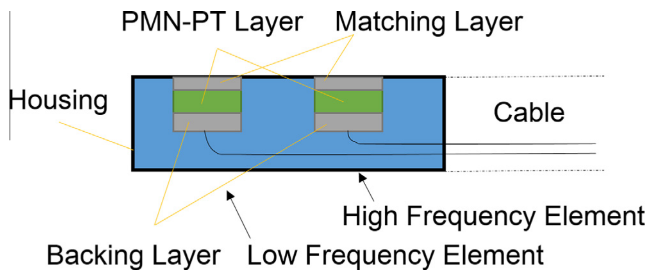

Fig. 1. Schematic diagram of the dual-frequency ultrasonic probe.

A novel imaging method by integrating two ultrasonic transducers with different center frequencies is proposed in this paper. Previously a single element transducer was proposed with dual-frequency (20/40 MHz) operation, which was optimized for tissue harmonic imaging [12]. A dual-frequency (6.5/30 MHz) transducer arrangement was also utilized for exciting microbubbles at low frequencies and detecting their broadband harmonics at high frequencies [13]. The proposed catheter in this paper combines both high-frequency ultrasonic element and relative low-frequency one. It has the ability to balance both imaging resolution and penetration depth. The center frequency of one transducer is 36 MHz, and the other one is 78 MHz. Lead magnesium niobate–lead titanate (PMN–PT) single crystal was selected due to its good piezoelectric properties (piezoelectric constant d_{33} ~2000 pC/N and electromechanical coupling coefficient k_t ~60%) compared to the conventional PZT ceramics, which is more suitable for high-performance ultrasonic transducers applications [11,13–16].

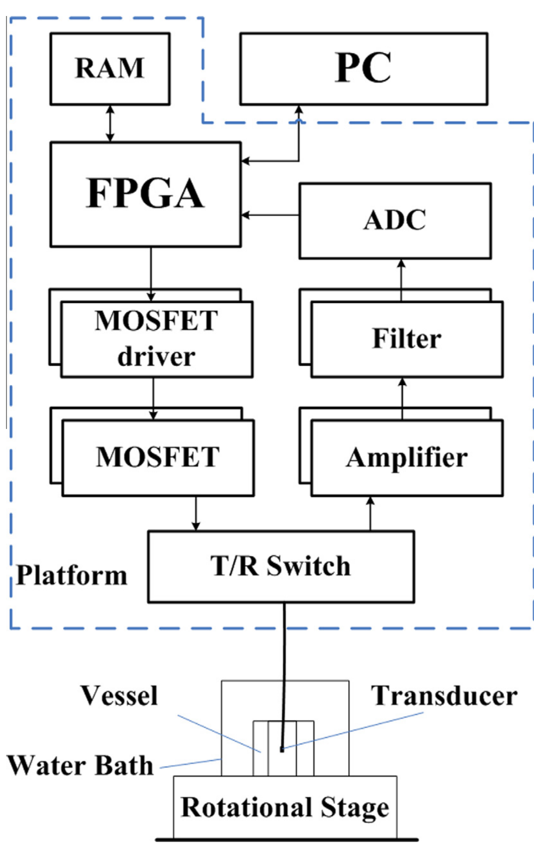

Fig. 2. The block diagram of the dual-channel imaging platform for IVUS applications.

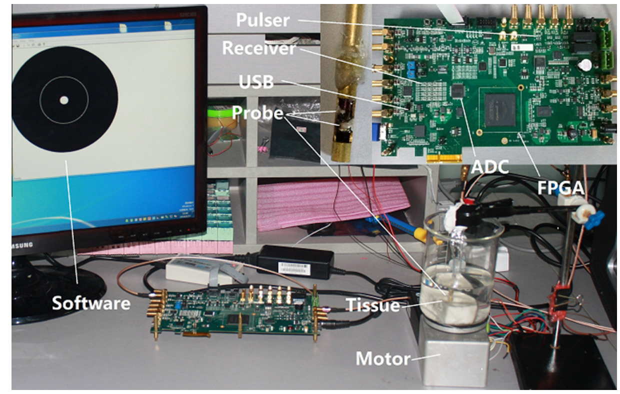

Fig. 3. Photograph of the dual-frequency ultrasonic probe, dual-channel imaging platform and experimental setup.

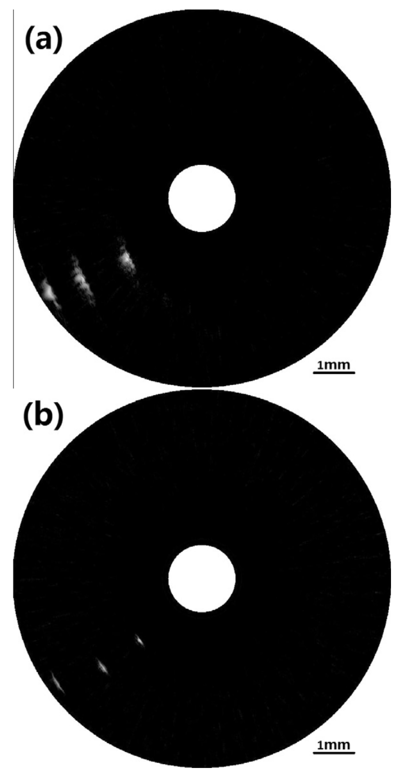

Fig. 4. Wire phantom evaluation of the dual-frequency IVUS platform. (a) Image acquired by low frequency ultrasonic element and (b) image acquired by high frequency ultrasonic element.

In terms of imaging system, a dual-channel imaging platform with programmable ability is proposed to process the dual-frequency ultrasound images, i.e., dual-channel data acquisition and imaging process can be achieved simultaneously. Field programmable gate array (FPGA) is employed as a core microprocessor to accomplish flexible (programmable imaging algorithms) and real-time imaging. Universal serial bus (USB) is employed in this platform for fast data transmission (higher than 200 MB/s). Raw radio frequency (RF) data are also acquired during the experiment. The platform design is based on electronic components and printed circuit board (PCB) for a compact (16.8 cm × 10.6 cm) implementation.

This paper is organized as follows, in Section 2, the fabrication of dual-frequency ultrasonic transducer and the development of