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Validation of an ultrasound transducer's generation and receiving function on one single-mode fiber

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ABSTRACT

This paper presents the design, fabrication and testing of a single-mode fiber optic ultrasound transducer. This transducer can work as an ultrasound generator and a receiver, based on principles of photoacoustic (PA) effect and Fabry–Pérot (FP) interference. PA effect is a process in which ultrasound waves are generated from optical energy by a PA material, and an FP structure is used for ultrasound receiving. The transducer was manufactured by coating a material called gold nanocomposite directly onto a single-mode optical fiber tip. The gold nanocomposite acted as the PA material and formed the FP structure as well. The transducer had the same size as the single-mode fiber, whose diameter was only 125 μm. It demonstrated its ability to generate ultrasound signals with a bandwidth of 5.6 MHz at an efficiency of 3.2×10^{-5} and function as an ultrasound receiver with a sensitivity of 2.81 mV/MPa. The generator and receiver built together can currently only work separately. This new transducer has substantial potential to work in restricted space and harsh environments for non-destructive testing.

1. Introduction

Ultrasound transducers have been widely employed in various applications such as nondestructive testing (NDT) and medical diagnostic imaging [1–7]. Compared to the traditional piezoelectric ultrasound transducers [8–11], optical ultrasound transducers, especially fiber optical ultrasound transducers are competitive in many occasions because of their compact size, immunity to electromagnetic interference (EMI) and survivability in high temperature/humidity environments [12].

The photoacoustic (PA) principle is the most commonly used mechanism to generate ultrasound optically. Briefly speaking, optical energy is absorbed within a material and then is converted into a localized temperature rise, which will finally lead to mechanical waves due to the material's thermal expansion [13,14]. Thus, a desired PA material is supposed to feature a strong ability for optical absorption and a large coefficient of thermal expansion (CTE). Many efforts have been put into obtaining higher-efficiency PA materials. Polymers, such as PDMS, become attractive because of their high CTE and flexibility of mixing with other materials. And nanoparticles made by noble metals have shown high optical absorption capacities at their plasmon resonant frequencies [15,16]. Therefore, researchers have combined these two different materials with different advantages (high CTE and strong optical absorption) together to achieve a high generation efficiency [16].

On the other hand, ultrasound has been optically received by structures such as the Fabry-Perot (FP) interferometer (also known as etalons) [17], fiber gratings [6], the Mach-Zehnder interferometer [18], and polymer micro-ring resonators [19] for decades. An FP interferometer that can work as an ultrasound receiver is basically formed by two partially reflecting mirrors [20]. The interferometer turns the ultrasound waves into the changes of the distance between two mirrors and finally into the optical spectrum phase shifts.

Since such mechanisms and structures can generate and receive ultrasound optically, some groups have integrated an ultrasound receiver with the generator to build an optical ultrasound generator and receiver on one single element. Hou et al. created an FP cavity using SU-8 material to add an ultrasound receiving function to an optical ultrasound generator [21]. In this device, SU-8 surrounded a black PDMS film, which acted as a generator, serving as a receiver array. Hou et al. also built another optical ultrasound transducer using gold nanoparticles [22]. The device consisted of three layers, a 2-D gold nanostructure followed by a PDMS layer and a gold layer. The gold nanostructure worked with PDMS to convert the optical energy into the thermal energy and finally into mechanical waves, while the gold layer and the gold nanostructures acted together as two reflected mirrors to form an FP structure to receive

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ultrasound echoes. Sheaff and Ashkenazi fabricated an all-optical ultrasound transducer by combining a polyimide thin film with an SU-8 FP cavity [23]. When excited, the polyimide layer generated ultrasound, and the SU-8 layer coated above the polyimide received ultrasound.

However, all these structures above were on glass substrates instead of optical fibers. Some other groups achieved fiber optic ultrasound transducers by using two fibers as the generator and the receiver, respectively. Biagi et al. coated epoxy mixing with graphite on the tip of a 600-μm-core multimode fiber to make an ultrasound generator, and received ultrasound using another single-mode fiber with an FP cavity [24]. This two-fiber transducer obtained C-mode image of a salami slice. Zou et al. characterized a PDMS thin film's resonant frequencies by using a 400-μm-core multimode fiber as the ultrasound generator and a single-mode fiber ultrasound receiver with an FP structure [25]. Placing these two fibers oppositely on different sides of the film and the resonant frequencies of the film allowed the calculation from the acquired ultrasound signals. Desjardins et al. fabricated an optical ultrasound transducer for vascular tissue 2D b-mode imaging [26]. A 200-μm-core multimode fiber coated with carbon nanotube composite generated ultrasound and an adjacent single-mode optical fiber with an FP cavity on its end face received the ultrasound. Noimark et al. fabricated composite coatings comprising PDMS and multiwalled carbon nanotubes and coated the distal ends of a 200-μm fiber [27]. A fiber-optic ultrasound receiver was paired with it to acquire all-optical pulse-echo images of aortic tissue. Finlay et al. generated ultrasound with a multiwalled carbon nanotube-PDMS coating on the end of a 300-μm fiber and received ultrasound with a FP cavity created by dip-coating a single mode fiber with optically transparent polymer [28,29]. These components can be integrated into medical devices to provide real-time image guidance. Belsito and Vannacci et al. applied micro-opto-mechanical-system (MOMS) technology to create patterned carbon films on miniaturized single-crystal silicon frames and built an ultrasound emitter on the tip of an optical fiber [30]. The emitter worked together with a fiber optical ultrasound detector, which was also fabricated by MOMS on a micromachined silicon frame, to compose a minimally invasive probe for endoscopic tissue analysis [31]. Table 1 summaries the characteristics of above-mentioned generators, receivers, and the combined transducers.

The transducers have been improved by using higher-efficient PA materials and broader bandwidth receiver to achieve higher resolution. Even so, these applications used two kinds of fibers, including a multimode fiber with a large diameter, which meant that the fabrication of the transmission elements and detection elements was separate. To the best knowledge of the author, no structure has been developed to build both an ultrasound generator and a receiver on a single-mode fiber. There are several advantages of achieving this: (1) capacity of working in very narrow space due to the tiny size of the single-mode fiber (OD: 125 μm); (2) simplification of the fabrication process because only one kind fiber and structure is applied.

In this study we first developed an ultrasound transducer on the tip of a single-mode fiber using gold nanocomposite. The gold nanocomposite worked as the PA material in the ultrasound generation procedure and formed an FP interferometer for the ultrasound receiving procedure. These two procedures were verified and tested respectively. Therefore, a novel optical ultrasound transducer built on a single-mode fiber that can work as a generator and a receiver has been created.

2. Methodology

2.1. Principles

In the ultrasound generation procedure, the amplitude of the generated ultrasound is described as [13,15]:

$$\left|\tilde{p}\right| \approx \alpha\beta_3\sqrt{B_3\rho_3}\left|\frac{s\tilde{I}}{K_1p_1 + K_3p_3 + C_2\omega\rho_2 s}\right| \tag{1}$$

Table 1
Summary of the characteristics of fiber optic ultrasound transducers.

Generator					Receiver	Combined transducer
PA material	Core size (μm)	Peak pressure (MPa)	Bandwidth (MHz)	Laser density (mJ/cm^2)	Bandwidth (MHz)	Resolution (μm)
Epoxy mixing with graphite [24]	600	0.15	Over 50	3.5	No less than 20	100
PDMS mixing with gold salt [25]	400	0.19	3.1	13	Air: 4.11;Water: 2.08	–
Carbon nanotube composite [26]	200	4.5	15	35	20	lateral: 88; axial: 64
PDMS mixing carbon nanotubes [27]	200	1.36	39.8	33.1	80	–
PDMS mixing carbon nanotubes [28]	300	8	26.5	28	80	64
Patterned carbon films by MOMS [30,31]	200	1.2	More than 40	40	10	70