Broad-band, high-efficiency optoacoustic generation using a novel photonic crystal-metallic structure

Yunbo Guo*[a,b], Hyoung Won Baac[b], Sung-Liang Chen[b], Theodore B. Norris[a,b], and L. Jay Guo[b]

[a] Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109-2099, USA
[b] Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109-2122, USA

ABSTRACT

Various optical structures have been investigated for high-frequency optoacoustic generation via thermoelastic effect, including metal films, mixture of polydimethylsiloxane (PDMS) and carbon black, two-dimensional (2-D) gold nanostructure with PDMS film, etc. However, they suffer from either low light absorption efficiency which affects the amplitude of generated ultrasound, or thick films that attenuate the amplitude and restrict its spectra bandwidth. Here we propose a novel one-dimensional photonic crystal-metallic (PCM) structure, which can be designed to absorb 100% optical energy of specific wavelengths in a total-internal-reflection geometry. The unique configuration enables us to choose suitable polymer films on top of the metallic structure, which can act as an ideal ultrasound transmitter to generate broad-band ultrasound with high conversion efficiency. Experimental results show that the PCM structure generated several times stronger ultrasound pressure than our previously demonstrated 2-D gold nanostructures [Appl. Phys. Lett. 89, 093901 (2006)]. Moreover, the generated ultrasound exhibited almost the same frequency spectrum as the input laser pulse (duration width 6 ns). This shows that the PCM structure has great potential to generate broad-band ultrasound signal. It is also important to mention that the simple PCM structure with the polymer film forms a Fabry-Pérot resonator and can play a role of an ultrasound receiver, which provides a convenient method to construct a broad-band and all-optical ultrasound transducer.

Keywords: Optoacoustic transducer, ultrasound transmitter, ultrasound detector, photonic crystal, metallic structure, total internal reflection, broad-band, all-optical, high frequency

1. INTRODUCTION

There is a strong demand that high-resolution imaging techniques obtain comprehensive morphological and functional information of important biological or industrial samples [1, 2]. Currently, the unavailability of two-dimensional (2-D) high-frequency transducer arrays (> 50 MHz) is a major bottleneck preventing further development of high-frequency ultrasound, especially in real-time 3-D high-resolution applications [3]. Piezoelectric ultrasound transducers are the currently dominant products on the market. Piezoelectric technology uses electronic signals to generate and detect ultrasound in piezoelectric materials (such as ceramic). It is mature for piezoelectric transducer arrays operating at less than 10 MHz, but it is extremely difficult to produce 2-D arrays operating above 20 MHz. The major problems for piezoelectric technology include the difficulty of cutting piezoceramic materials to micrometer-scale elements in order to get high frequency ultrasound, electrical connections to small elements, crosstalk between elements, and increased detection noise with reduced element size, as well as the lack of quality high frequency materials and electronics.

Using optical methods to generate and detect ultrasound is an attractive technology and has been investigated for years [4, 5]. However, most of the optical methods could only generate or detect high frequency ultrasound on separate transducer elements. The current state-of-the-art, all-optical ultrasound transducer was based on a two-dimensional gold nanostructure [6]. It can absorb 30% of the light energy of a laser pulse for ultrasound generation and transmit 90% at the wavelength of a probe laser so that it can be part of a Fabry-Pérot cavity for ultrasound detection, which allows an optoacoustic generator and detector to be integrated into the same transducer. However, its fabrication process is much more complicated and expensive than with piezoelectric technologies, and its ultrasound generation efficiency is low and the detection sensitivity is not high.

* Email: guoybyw@umich.edu; Phone: (973)780-7182; Fax: (734)763-4876

Photons Plus Ultrasound: Imaging and Sensing 2011, edited by Alexander A. Oraevsky, Lihong V. Wang, Proc. of SPIE Vol. 7899, 78992C · © 2011 SPIE · CCC code: 1605-7422/11/$18 · doi: 10.1117/12.876012

We have proposed an innovative photonic crystal-metallic (PCM) structure which provides many unique advantages for high frequency ultrasound generation and detection [7]. It can act as an ideal ultrasound transmitter which absorbs 100% of the energy of the laser pulse to generate a stronger broad-band ultrasound signal than the complicated 2-D gold nanostructures; at the same time, it can also be used as a high-sensitivity optoacoustic receiver to the reflected ultrasound. Moreover, it has a simple configuration which is very easy to fabricate with current fabrication technology and with very low cost.

In this paper, we concentrate on using the photonic crystal-metallic structure to develop a broad-band, high-efficiency optoacoustic transmitter. We first discuss how to obtain an ideal ultrasound transmitter using optical methods, then introduce the photonic crystal-metallic structure and explore its operating principle for ultrasound generation. Moreover, we experimentally demonstrate that the PCM structure is able to generate strong, broad-band ultrasound with high efficiency.

2. OPTOACOUSTIC TRANSMITTER

A variety of mechanisms have been studied for optical generation of ultrasound, and the most common and efficient one is thermoelastic effect, where the key component is a light-absorbing film deposited on a transparent substrate [8, 9]. The typical procedure of optical ultrasound generation can be described as follows: a laser pulse is injected onto the film surface, and the film absorbs the laser pulse energy, then optical absorption rapidly causes a temperature rise in a localized volume in the film, where thermal expansion launches an acoustic wave into the overlying sample. The biggest advantage of thermoelastic effect is that the acoustic pressure in the far field is proportional to the time derivative of the laser pulse, meaning that the center frequency and bandwidth of the generated ultrasound is mainly determined by the incident laser pulse; thus, acoustic waves with desired properties can be achieved simply by modulating the optical input. In addition, the far field acoustic pressure generated by an incident laser pulse can be theoretically described as [9]:

$$P_{far} = \frac{1}{4\pi}\frac{3B^2\alpha_L}{\rho^2 c^2 C}\frac{1}{r}\frac{dI(t-\frac{r}{c})}{dt} \propto \frac{dI(t)}{dt}$$

where B is the bulk modulus, ρ is the density, αL is the linear coefficient of thermal expansion, c is the longitudinal wave speed in the medium, C is the specific heat capacity, I is the total optical energy incident onto the film, and r is the distance from the surface.

Previous studies of thermoelastic expansion for optical generation of ultrasound had concentrated on utilizing metal films to generate acoustic waves because they are effective optical absorber. However, their thermal expansion coefficients are generally low in the range of $0.1\sim0.2\times10^{-4}$/K, which limited the transduction efficiency [8]. Obviously, high transduction efficiency can be significantly improved by using materials with higher thermal expansion coefficients like polydimethylsiloxane (PDMS), which has a coefficient of 3.1×10^{-4}/K, more than ten times higher than common metals. However, PDMS is a transparent polymer, thus does not absorb optical energy. Hou et al. used a spin-cast film consisting of a mixture of carbon black and PDMS where carbon black was used as the optical absorber, and increased the optoacoustic conversion efficiency by more than 30 dB compared to a metallic one [9]. However, the increased viscosity due to mixing PDMS with carbon black limits the spin-cast film thickness to 11 μm, which restricted the bandwidth and amplitude of the generated ultrasound because only less than 1 μm PDMS layer from the substrate contributed to the thermoelastic effect and other overlying PDMS just attenuated the generated ultrasound by roughly 1 dB/μm. Furthermore, Hou et al. developed a 2-D gold nanostructure as optical absorber with a 3~4 μm PDMS film. Although low light absorption efficiency (~30%), it improved the generated optoacoustic bandwidth to 57 MHz and acoustic surface pressure to 100 MPa [6, 10]. Recently, Baac et al. used a carbon nanotube-PDMS composite with 2.6 μm film thickness, and achieved 18 times stronger optoacoustic pressure than a metal film and a broadband frequency range [11].

An ideal ultrasound transmitter should be made of 100% optical absorber with large thermal expansion coefficient, low heat capacity and near-water acoustic impedance. Here we summarized several important parameters of different materials affecting the ultrasound generation in Table 1. Obviously, only using the metal film is not effective for ultrasound generation as demonstrated in previous studies. The combination of metal or carbon compounds and thin polymer (PDMS, PMMA) may be a better choice, like gold film with PDMS layer on the top. Further improvement can be achieved with larger light absorption efficiency and thinner polymer film thickness.

Table 1. Optical, thermal and acoustic properties of materials

Materials	Optical absorber	Thermal conductivity W/(m•K)	Thermal expansion coefficient α_L 10^{-4} m/(m•K)	Specific heat capacity J/(g·K)	Young's Modulus E	Acoustic Impedances Z (MRayl)	Acoustic Velocity (m/s)
Air	NO	0.025	--	1.0035	0.1 MPa	0.42×10^{-3}	340
Water	NO	0.6	0.69	4.1855	2.2 GPa	1.483	1480
Glass	NO	1.1	0.085	0.8436	73 GPa	15.3	5700
PDMS	NO	0.15	3.1	1.5	0.75~5 MPa	1.90	1000
PMMA	NO	0.167~0.25	0.5~0.9	1.48	900 MPa	3.23	2740
PVDF	NO	0.17-0.19	0.42	1. 17 – 1.51	4 GPa	4.2	2300
Chromium	YES	93.9	0.06	0.449	279 GPa	30.5	5940
Gold	YES	318	0.14	0.129	78 GPa	63.8	3240
Silver	YES	429	0.18	0.233	83 GPa	38.0	3600
Carbon graphite	YES	140	0.065 (//) 0.005 (⊥)	0.71	10 GPa	7.31	--
Carbon nanotube	YES	3000~3500	-0.015±0.02	---	1 TPa	--	--
Graphene	YES	5300	---	---	0.95~1.1TPa	--	--

3. PHOTONIC CRYSTAL-METALLIC STRUCTURE

Figure 1 shows the schematic of the photonic crystal-metallic structure. It consists of a one-dimensional photonic crystal structure (i.e. alternating multiple dielectric layers including a defect layer) with an adjacent metallic structure (like metal layer) on the top, which is operated in a total-internal-reflection (TIR) geometry. The total internal reflection happens on the interface between the defect layer and the metal layer, and a Fabry-Pérot resonator forms in the defect layer due to the high reflectivity provided by both the PC structure and the TIR boundary, similar to the photonic crystal-total internal reflection (PC-TIR) structure we demonstrated before [12]. However, since there is a metal layer on the top of the FP resonator in a TIR geometry, surface plasmons can be excited by some of the FP resonant modes.

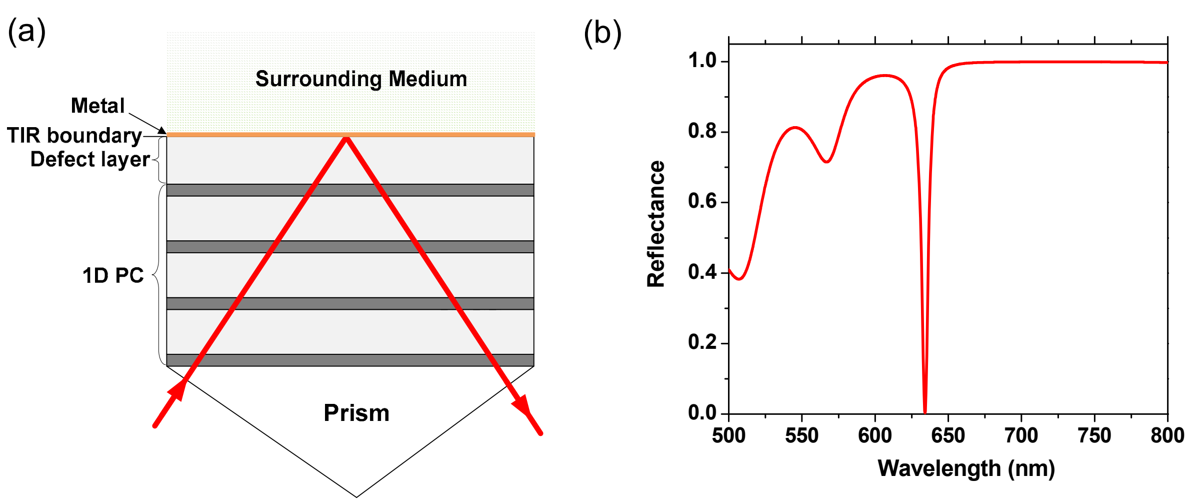

Fig. 1. (a) Schematic of a PCM structure. (b) The simulated reflectance spectra of the PCM structure

Surface plasmons are waves that propagate along the metal surface, and they are essentially *p* polarized light waves that are trapped on the surface because of their interaction with the free electrons of the metal. This part of light is normally transferred into heat within the metal film and gets lost. As Figure 1 (b) shows, the excited plasmon mode can be characterized by a resonance dip in the reflectance spectra, similar to surface-plasmon-resonance (SPR) based sensors [13]. Moreover, the mode satisfies the conditions for both the existence of the resonance mode in the Fabry-Pérot cavity and the plasmon mode in the metallic structure. By choosing a suitable PC structure and the metal layer thickness, light from specific wavelengths can be totally absorbed by the PC-metallic structure (see Fig. 1b).

If we put sensitive polymer materials such as polydimethylsiloxane (PDMS) on top of the metallic structure (normally by spin coating), as Figure 2 (a) shows, the incident light (for example, a laser pulse) will be absorbed and be transferred into heat which can be used to generate an ultrasound signal in the polymer material via a thermo-elastic effect. However, adding one more polymer layer (normally μm thickness) may change the properties of the PCM structure. It turns out that there exists another total internal reflection boundary between the polymer and the surrounding medium (i.e. water), and that one more Fabry-Pérot resonator is formed in the polymer layer with the TIR boundary and the metal surface. Therefore, the final modes have to satisfy all of the three resonant conditions. As Figure 2(b) shows, with the increase of the polymer thickness, the resonance dip becomes narrower and narrower. The results also show that the PCM structure with polymer layer is still able to totally absorb the input light at specific wavelengths for ultrasound generation. In addition, a fundamental resonance dip appears in the reflectance spectrum corresponding to the excited mode (the absorbed part), which can be used for ultrasound detection [7, 14]. In this way, all-optical ultrasound transducer can be achieved with this structure.

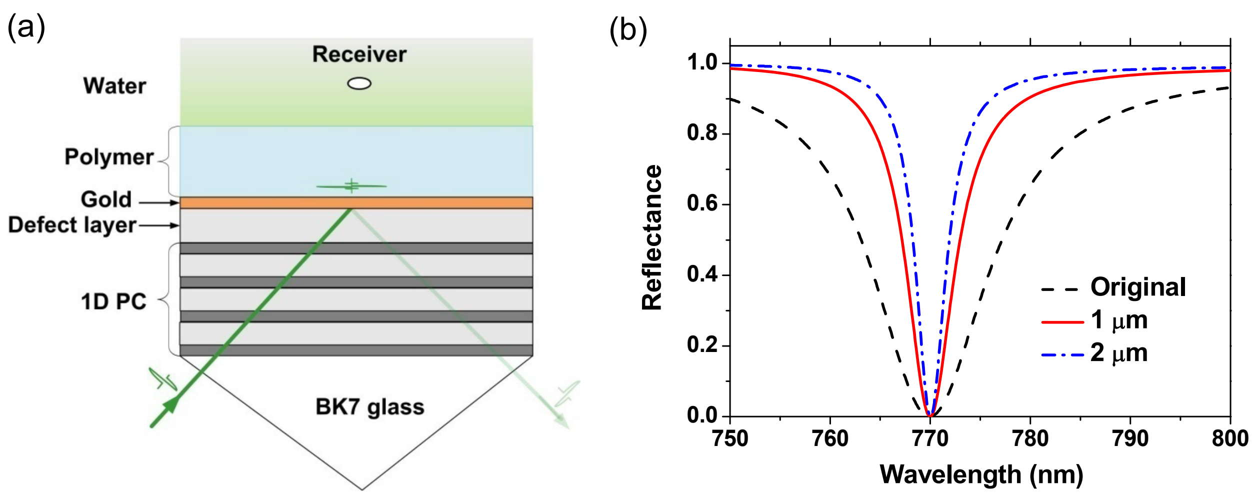

Fig. 2. (a) Schematic of an optoacoustic transmitter using PCM structure with polymer layer.
(b) The simulated reflectance spectra of the PCM structure with different thickness polymer layers.

As we discussed above, we need effective light absorber and large thermal expansion coefficient polymer material to get an ideal optoacoustic transmitter. The unique PCM structure provides many advantages for optoacoustic generation. First, by designing the PCM structure and the polymer layer, we are able to get the largest absorption (100%) at the wavelength of the pulse laser. Second, the open cavity configuration allows us to choose large thermal expansion coefficient polymer to get high sensitivity, without decreasing the cavity finesse like etalon sensors. Third, the polymer is totally open to the surrounding medium, and its thickness could be very thin (~ 1 μm) so that it won't attenuate generated optoacoustic signal and affect the frequency response. Fourth, the PCM structure is operated in a total-internal-reflection geometry. With most of the incident light absorbed by the structure and the remaining part reflected back, there won't be any light injecting on the object (on the top). It means that our structure can use as high as possible laser pulse power to generate strong ultrasound signal but would not do harm to the object; on the contrary, for almost all the current optoacoustic methods, the laser pulse is normally injected on the film or human objects. Due to poor light absorption efficiency, a little part of light is absorbed, but most of the light transmits through the film and injects on the object, which may cause damage to it. The maximum permissible pulse energy and the maximum permissible pulse repetition rate are governed by the ANSI laser safety standards, which are typically at least an order of magnitude less than the damage thresholds. In this way, our structure has a great advantage to achieve much stronger ultrasound for clinical use. Fifth, the unique PCM structure allows us to operate the ultrasound transducer at any wavelength, giving much more flexibility to choose pulse laser sources. Furthermore, the whole structure can be fabricated easily by thin film deposition and polymer spin coating methods with very low cost.

4. EXPERIMENTS

In order to experimentally demonstrate it, we designed and fabricated the PCM structure as follows: substrate / TiO_2 / $(SiO_2/TiO_2)^3$/ X / Ti / Au. The 1-D PC structure was made of alternating 87-nm TiO_2 layer and 286.5-nm SiO_2 layer; the "defect" layer X was composed of another 165-nm SiO_2 layer, and the metallic structure was 15-nm gold layer with 1-nm Ti film as the adhesive layer. The structure was fabricated by electron beam deposition on a flat BK-7 glass substrate. After that, we spin coat a 2.03-μm PDMS transparent film (adjacent to gold layer) on top of the whole structure. The laser source is a pulsed laser with 532 nm wavelength, 6 ~ 10 ns pulse duration width and 20 Hz repetition rate (Surelite I-20, Continuum, Santa Clara, CA). The PC-Metallic structure was put on a prism via index-matching liquid. When the incident angle in the substrate was 64^o and the top surface was covered by DI water, we measured the reflectance spectrum with a white light source (*p* polarization) and a spectrometer. As shown in Figure 3, although there were some differences between the experimental results and the simulation for the 2nd or 3rd dip due to the non-uniformity of the spin coated PDMS film, the first dip at 532 nm was fitted well by the simulation, and the reflectance was 10%, which meant that about 90% light from the wavelength of 532 nm was absorbed by the structure.

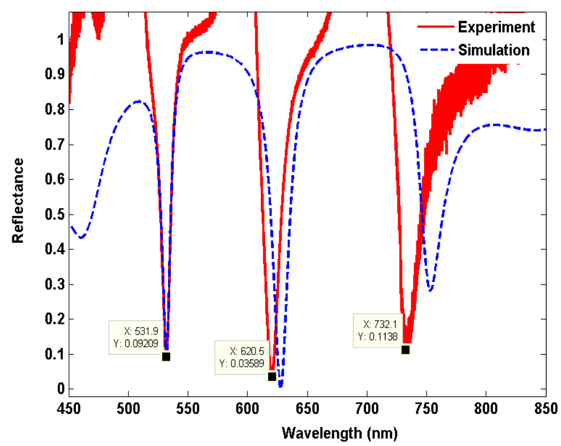

Fig. 3. Experimental and simulated reflectance spectra of PCM with PDMS film.

Then we changed to the pulsed laser (532nm, 10 ns) and performed a series of experiments to check the generated ultrasound.

1) We used a standard piezoelectric transducer (20 MHz, flat) as the ultrasound detector to calibrate the generated acoustic amplitude. The probe beam diameter size was 1 mm and the transducer in DI-water was 1.5 mm far from the PDMS surface. After amplified by 32 dB, the detected signal was directly recorded without average and shown in Figure 4 (a). When the laser wavelength 532 nm was out of the resonance dip (off-resonance), there was no light absorbed in the structure, so no ultrasound was generated as expected; when the laser wavelength 532 nm was on resonance, about 90% of the injected laser pulse energy was absorbed and used to generate ultrasound. Very strong ultrasound signal was observed as Figure 4(a) shows, and the generated acoustic pressure (amplitude) at the far field was linearly proportional to the power of laser pulsed energy (Figure 4b). That means that we can always achieve a much higher acoustic pressure by increasing the pulsed laser power as soon as it is below the thermal threshold. As discussed above, it is a big advantage for our PCM structure operated in TIR geometry.

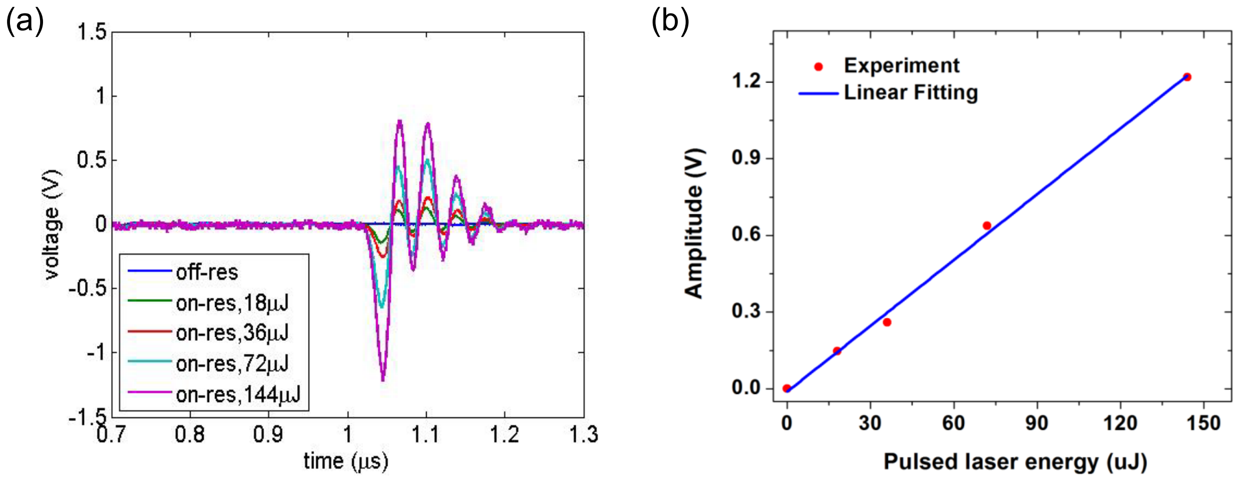

Fig.4. (a) Generated ultrasound signal with different input pulse laser energy;
(b) Generated ultrasound amplitude vs. the input pulse laser energy.

2) We used a polymer microring resonator as the ultrasound detector to calibrate the generated acoustic waveform and pressure. The polymer microring resonator was demonstrated to have high ultrasound detection sensitivity and a wide detection bandwidth of over 90MHz at -3 dB [15]. Since the microring resonator size was very small (~100 μm) and was sensitive to the ultrasound from different angles, the position relative to the generator surface was critical. Here we tested the generated ultrasound with different laser spot sizes (diameter 1 mm & 5 mm) with the same incident optical fluence (23 mJ/cm^2). With the amplification of 16 dB by photodetector, the ultrasound signal was directly recorded without average. High SNR indicates that strong ultrasound was generated (as Figure 5 shows).

The measured signal amplitude was 0.72 V for 1 mm spot size, so the original signal was 18 mV without amplification. Considering that the microring had a sensitivity of 150 pm/MPa and the microring resonance dip shifts 36 pm with the slope of 0.5 mV/pm, we calculated that the acoustic pressure at 1.16 mm was 240 kPa. Taking into account the attenuation in water (0.0022 dB/cm/MHz^2), the acoustic pressure at 10 mm was about 28 kPa, which was one order of magnitude higher than the 2D gold nanostructure film (the current state-of-the-art result) [10].

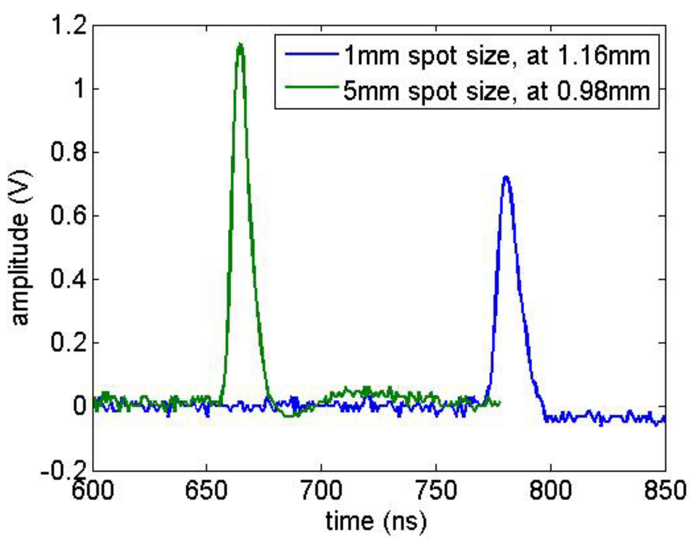

Fig. 5. Generated ultrasound signal measured by polymer microring resonator with 1 mm and 5 mm probe spot sizes.

We also investigated the frequency-domain performance of the optoacoustic transmitter over broadband frequency. In this experiment, we used a shorter laser pulse 6 ns and more uniform PMMA film (2-µm-thick) as the sensitive polymer layer. As Figure 6 (a) shows, the optoacoustically generated ultrasound wave by the PCM/PMMA composite almost replicated that of the laser pulse. Based on the measured ultrasound pulse waveforms, we also obtained the corresponding frequency spectra. As shown in Figure 6(b), the generated ultrasound has a broad-band frequency spectrum as the laser pulse up to 78 MHz at -6 dB. Obviously, much broader bandwidth could be achieved in the PCM structure with a narrower laser pulse (like 2 ns for 250MHz bandwidth at -6 dB).

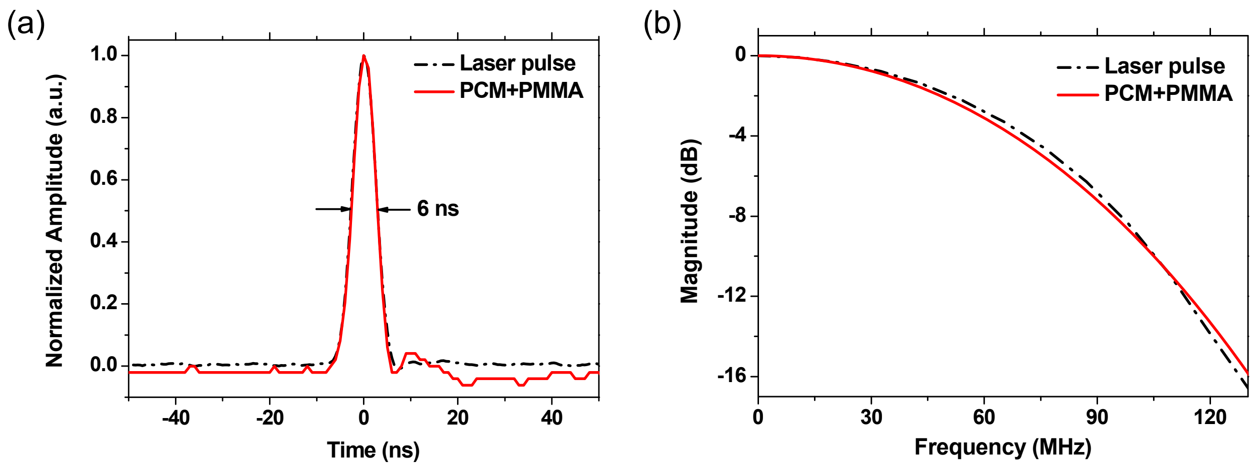

Fig. 6. Comparison between laser pulse and detected ultrasound for (a) signal (b) spectrum

5. CONCLUSION

To summarize, we have proposed and developed a novel optoacoustic transmitter based on photonic crystal-metallic structure in a total-internal-reflection configuration. The PCM structure introduced a new plasmonic excitation method and could be designed to achieve 100% light absorption at specific wavelengths, which greatly improve the efficiency of optoacoustic generation. Operated in TIR geometry, this structure exhibited a large flexibility in choosing suitable polymer films for broad-band, high-pressure ultrasound generation. The composite of PCM and PDMS achieved one order of magnitude higher ultrasound signal than the 2D gold nanostructure film (the current state-of-the-art result), while the composite of PCM and PMMA generated an ultrasound waveform same as that of the laser pulse, and showed a broad-band frequency spectrum up to 78 MHz at -6dB, which can be further improved by simply shortening the laser pulse duration width.

Most important, this PCM structure can also act as a highly-sensitive ultrasound detector. Therefore, we can integrate ultrasound transmitter and receiver on the same structure and develop an all-optical ultrasound transducer, which provides many distinct advantages. We can use high power pulse laser to generate strong acoustic waves, without damaging the objects. Open cavity configuration also allows to choose low Young's modulus polymer material to get high sensitivity, without decreasing the cavity finesse like etalon sensors. What's more, the unique PCM structure can be operated at any wavelength, giving much more flexibility to choose pulse laser and cw laser sources, which is very helpful for applications and commercialization. We believe that the PCM structure is very promising to develop broad-band, all-optical ultrasound transducer arrays for high resolution, 3-D ultrasound imaging, and will have great impacts on medical imaging, biomedical research and industrial applications.

ACKNOWLEDEGEMENT

This project has been funded by Rackham Graduate Student Research Grant from the University of Michigan.

REFERENCE

[1] Lockwood, G. R., Turnball, D. H., Christopher, D. A., and Foster, F. S., "Beyond 30 MHz applications of high-frequency ultrasound imaging," IEEE Eng. Med. Biol. 15(6), 60-71 (1996).

[2] Wells, P. N. T., "Ultrasound imaging," J. of Biomed. Eng. 10(6), 548-554 (1988).

[3] Foster, F. S., Pavlin, C. J., Harasiewicz, K. A., Christopher, D. A., and Turnbull, D. H., "Advances in ultrasound biomicroscopy," Ultrasound Med. Biol. 26(1), 1-27 (2000).

[4] Sorazu, B., Thursby, G., Culshaw, B., Dong, F., Pierce, S. G., Yang, Y., and Betz, D., "Optical Generation and Detection of Ultrasound," Strain 39(3), 111-114 (2003).

[5] Wang, L., [Photoacoustic Imaging and Spectroscopy] CRC Press (2009).

[6] Hou, Y., Kim, J.-S., Ashkenazi, S., Huang, S.-W., Guo, L. J., and O'Donnell, M., "Broadband all-optical ultrasound transducers," Appl. Phys. Lett. 91(7), 073507-3 (2007).

[7] Guo, Y., Norris, T. B., Baker, J. R., Guo, L. J., and Walter, N. G., "Photonic Crystal - Metallic Structures and Applications, " US Provisional Patent Application No. 61/349,440 (2010).

[8] Buma, T., Spisar, M., and O'Donnell, M., "High-frequency ultrasound array element using thermoelastic expansion in an elastomeric film," Appl. Phys. Lett. 79(4), 548-550 (2001).

[9] Yang, H., Ashkenazi, S., Sheng-Wen, H., and O'Donnell, M., "Improvements in optical generation of high-frequency ultrasound," IEEE T. Ultrason. Ferr. 54(3), 682-686 (2007).

[10] Hou, Y., Kim, J.-S., Ashkenazi, S., O'Donnell, M., and Guo, L. J., "Optical generation of high frequency ultrasound using two-dimensional gold nanostructure," Appl. Phys. Lett. 89(9), 093901-3 (2006).

[11] Baac, H. W., Ok, J. G., Park, H. J., Ling, T., Chen, S. L., Hart, A. J., and Guo, L. J., "Carbon nanotube composite optoacoustic transmitters for strong and high frequency ultrasound generation," Appl. Phys. Lett. 97(23), 234104-3 (2010).

[12] Guo, Y., Divin, C., Myc, A., Terry Jr, F. L., Baker Jr, J. R., Norris, T. B., and Ye, J. Y., "Sensitive molecular binding assay using aphotonic crystal structure in total internalreflection," Opt. Express 16(16), 11741-11749 (2008).

[13] Skorobogatiy, M. A., and Kabashin, A., "Plasmon excitation by the Gaussian-like core mode of a photonic crystal waveguide," Opt. Express 14(18), 8419-8424 (2006).

[14] Chow, C. M., Zhou, Y., Guo, Y., Norris, T. B., Wang, X., Deng, C. X., and Ye, J. Y., "High-frequency ultrasonic sensor using an open-cavity photonic crystal structure," J. Biomed. Opt. (accepted).

[15] Huang, S.-W., Chen, S.-L., Ling, T., Maxwell, A., Odonnell, M., Guo, L. J., and Ashkenazi, S., "Low-noise wideband ultrasound detection using polymer microring resonators," Appl. Phys. Lett. 92(19), 193509-193509-3 (2008).