Optical MEMs transducers with enhanced efficiency and sensitivity

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Abstract. We introduce a highly sensitive laser ultrasonic detection MEMs transducer and an efficient laser ultrasound generation MEMs transducer. The detection transducer consists of a series of cantilevers with the same dimensions; any two cantilevers next to each other are separated by a solid with the same width as finger’s. When ultrasound is incident upon this transducer, as long as there is a vibration component perpendicular to each finger’s top surface and with a frequency the same as the finger’s first resonance in the ultrasound, each finger will resonate upon the ultrasound. The moving fingers and the still solid separations form an optical phase grating, and therefore the ultrasound can be readout by a detection laser remotely. Because the ultrasound amplitude is amplified many times by the transducer’s resonance before detection, the sensitivity of this transducer is much higher than that of traditional transducers.

The generation transducer consists of a micro-disk seated upon a micro-stem. When a suitably focused laser pulse illuminated on the center of the disk, a certain order of flapping motion of the disk is mainly actuated, while other orders are just slightly, or not excited. This flapping motion couples a very narrow bandwidth of longitudinal wave propagating along the axis of the stem and into a sample. Because all absorbed optical energy is concentrated into this narrowband ultrasound, its amplitude is much higher than that of normal thermoelastic generation. It is possible to use these MEMs generation and detection transducers to form a simple but highly efficient laser ultrasound generation and detection system in the near future

1. Introduction

Laser based ultrasonic techniques have been paid great attention in recent decades. This is because laser ultrasonic inspection has advantages over traditional ultrasound generation and detection that are based on contact techniques. The ability to operate remotely from the sample surface makes the non-contact and couplant-free online generation and detection of ultrasound possible, allowing inspection of areas where access is difficult [1]. However, compared with conventional ultrasound techniques, the SNR of laser ultrasound is low due to the shot noise of optical detection. Raising the power of the laser pulse to produce ultrasound with a higher amplitude is one of the solutions; however this is constrained by the damage limit [2]. Great efforts have been made to overcome this drawback in the last two decades by either increasing the amplitude of the laser ultrasound or strengthening the detection sensitivity, or both [3, 4, 5].

In order to remotely generate and detect laser ultrasound, different complex and expensive systems have been developed, as was reviewed in [3], such as confocal Fabry-Perot interferometers, photo-emf detectors, electromagnetic acoustic transducers and knife-edge
detectors [6]. This also leads to the development of hybrid ultrasonic systems [4]. For detection of ultrasound with high sensitivity, a cantilever optical MEMs detection transducer with a sensitivity a few hundreds times higher than that of the conventional methods has been also reported recently [5].

In order to increase the amplitude of laser-generated ultrasound, different techniques have also been successfully developed. One technique is to deposit a layer of material, such as graphite, with a higher optical absorption coefficient onto the surface of a sample [7]. This can effectively increase the absorbed optical energy. In [8], laser light was line-focused so that the optical power can be effectively increased while the power density of the laser pulse still remains within nondestructive regime. By combining the techniques in [7] and [8], generation transducers with patterned absorption layers have also been developed [9]; this can be applied to generate narrowband ultrasound with improved SNR. A different technique is to achieve higher amplitude by narrowing the bandwidth. This has been done by different methods; for instance different lasers were used to generate narrowband laser ultrasound [10, 11].

In addition to these, complex optical arrays [12, 13], special methods [14] and optical transducer systems [9] were also developed for the generation of narrowband ultrasound with higher amplitude/SNR.

In this paper, we present an optical MEMs detection transducer with high sensitivity and an optically powered MEMs generation transducer for the generation of narrowband ultrasound with high amplitude/SNR, providing a different solution to the optical shot noise problem for laser ultrasound generation and detection. The detection transducer is found to have a much higher sensitivity than that of traditional ones, and the generation transducer can produce narrow bandwidth ultrasound with a much higher amplitude than that of normal-thermoelastic generation at the same optical conditions.

2. The optical MEMs detection transducer
2.1. Analytical sensitivity of the detection transducer
The initial inspiration for the detection transducer came from experimental observations of anomalous ultrasonic responses of damaged coatings. Figure 1(left) shows a microphotograph and an acoustic scan of a ceramic sample with a damaged chrome coating. The coating was poorly adhered to the surface and peeled off using adhesive tape. At the edge of the damaged region there are delaminated regions of coating, some of which demonstrate very significant enhancements in an acoustic signal which is detected optically. These delaminated regions have, in response to the acoustic wave, a flap motion with a significantly higher amplitude than the surrounding bonded regions. The flap increases the amplitude of the vibration and because this occurs before optical readout it can increase the measured amplitude without increasing the noise. By combining this concept with a CHOT (cheap optical transducer) structure [9] we have produced an optically read ultrasonic transducer with high sensitivity as shown in figure 2. These transducers consist of several resonant ‘fingers’ that can be fabricated next to one or more solid spaces (usually the gaps between the fingers). This forms a zero-order interferometer where the normal ‘object’ beam is derived from the light reflected by the fingers and the normal ‘reference’ beam from the solid spaces adjacent to them. Normal construction uses several fingers which form an optical phase grating and generate discrete diffraction orders (if the pitch of the grating is less than the optical wavelength then these higher orders are evanescent)[9, 15]. The grating structure and presence of these orders make the optical detection simple as it is sufficient to place one of the diffracted orders (usually the zero-order) onto a photodetector to make the measurement. When an ultrasonic wave is incident on this device it causes the fingers to move, which changes the grating’s optical properties and therefore modulates the optical power diffracted into the various orders. The amplitude of the ultrasound is mechanically amplified by the fingers’ resonance from a few tens to several hundred times, depending on the material,
Figure 1. Evidence of amplitude enhancement by a loose structure. The image on the left shows a damaged coating (chrome on silicon nitride). At the edge of the damaged region there are delaminated areas of chrome. Scanning over these regions (dotted line) reveals significant amplitude enhancement at the delaminated region. The large amplitude (and phase change) suggests a resonant structure.

Figure 2. (a) Schematic design of a MEMs detection transducer. (b) and (c) Mechanical model of a finger of the MEMs transducer.

gometry and the working environment of the transducer. As this is done before detection, the sensitivity of the transducer to ultrasound is greatly enhanced.

Figure 2(right) shows the mechanical model of the finger of a detection transducer. From this model, analytically the sensitivity of the transducer is found out to be [5]:

\[
\gamma_1 = \frac{|w_1(l, t)|_{max}}{A_{am}} \approx 1.566Q_1,
\]

(1)

\[
\gamma_2 = \frac{|w_2(l, t)|_{max}}{A_{am}} \approx 0.868Q_2,
\]

(2)

\[
\gamma_3 = \frac{|w_3(l, t)|_{max}}{A_{am}} \approx 0.508Q_3,
\]

(3)

where \(\gamma_i\) (i=1,2,3) is the sensitivity of the transducer at \(i^{th}\) order of resonance, \(w_i(l, t)_{max}\) is the
maximum finger’s tip amplitude, $A_{\text{am}}$ is the amplitude of the ultrasound that is incident on, and $Q_i$ is finger’s quality factor at $i^{th}$ order resonance. Analytically, this type of transducers have high sensitivity. For details of the analysis, reference [5] can be referred to.

### 2.2. Design and fabrication of the transducer

Several different types of transducers were designed with frequency of 1 MHz, 2 MHz and 3 MHz respectively. Figure 3(i) shows the top view of the designed 10×10mm device. 24 transducers with various different structure types were designed onto the chip in two rows; a row of small transducers (top) and a row of large transducers (bottom). In each row there are four different types of structures, referred to as a, b, c and d types from right to left: $a$ type transducers consist of plain silicon fingers and separations. $b$ type transducers are based on $a$ type, plus a reference metal layer on the top surface of each separation. For $c$ type transducers, both the fingers and the separations are covered by the metal layer. $d$ type transducers have a thermal actuator on the top surface of each finger. In each of the four types of structure, there are three transducers with 1-, 3- and 5-MHz fingers respectively, arranged from left to right. We designed transducers with these four different structures in order to attempt different initial deflections of the fingers to satisfy the diffraction condition; these initial deflections can be different because of their different lengths and coatings [16, 17]. Finger lengths of transducers with the same resonance frequency are slightly different for different structure types due to the additional metal layer on the finger top surface; they were refined by finite element (FE) analysis.

The dimensions of each small transducer finger were approximately $(66 \sim 170) \times 50\mu m$ plus a
9\mu m air gap at each side of the finger. In order to satisfy the MEMSCAP design rules a large hole was opened up underneath the entire transducer (figure 3(j)∼(k)). This left the “solid” surfaces between the fingers as thin bridges across the hole. In addition there was a residual membrane on one side (figure 3(j)∼(k)). This has the disadvantage that resonances of the bridges and membrane exist and may be detected in addition to those of the fingers. However these could be exploited to extend or manipulate the frequency response of the transducer.

To overcome this limitation of the MEMSCAP process larger transducers were also fabricated. The dimensions of each big transducer finger are approximately (66 ~ 170) × 240\mu m plus a 30\mu m air gap at each side of the finger. The larger finger width allows the hole beneath the bridges and membrane to be removed leaving a simpler structure (figure 3(j) and (m)).

Transducers were fabricated using a typical MEMs process—a standard SOIMUMPs (Silicon on Insulator Micromachining Process) at MEMSCAP (Refer to http://www.memscap.com.) The fabrication material is (100) type of SOI (silicon on insulator) wafer with a crystal silicon design layer of thickness 25\mu m; this defines the finger thickness of the transducer. The primary flat direction of the wafer is (110) and the material properties of the wafer are defined in [18]. Figure 3((i)∼(m)) shows the designed transducers and their 3D structures details, and Figure 4(n) was an ultrasonically c-scanned image of a wafer with 24 detection transducers on it, and (o) and (p) of the figure are the images of fabricated transducers under a microscope to show local structural details of a transducer.

2.3. Experimental study of the MEMs detection transducer
The aim of the experiment was to confirm that an ultrasonic wave of a given frequency can be detected by using the appropriately designed transducer with high sensitivity, and to examine the transducer’s dynamic behavior. To do this, an optical measurement system was configured, as shown in figure 5. Collimated light from a laser (optical wavelength 532 nm) was used to illuminate the MEMs transducer. An optional cylindrical lens can be inserted to focus the light to a line and ensure a greater fraction of the light lands across the fingers. The reflected light and

Figure 4. (n) Ultrasonic c-scanned image of the wafer with fabricated 24 detection transducers. (o) and (p) Images of fabricated transducers under a microscope to show local structure details.
orders from the MEMs transducer travel back through the same optics and are diverted in turn to (1) a CCD which is used to image the sample and align the system, and to (2) a detection arm. In the detection arm the unwanted diffraction orders are removed by an iris. The remaining 0-order is then focused onto a photodiode for detection. The fabricated transducer was glued onto a carrier that was attached to a piezoelectric ultrasound generation transducer. We used a 5-MHz ‘Olympus V609-SB 5.0/0.5 Videoscan’ piezoelectric transducer with a bandwidth of about 110%. An RF signal generator was used to generate a signal to drive the piezoelectric transducer, which produces a required longitudinal wave to excite the sample.

2.3.1. Bandwidth measurements  The dynamic response of an \textit{a} type small transducer with 1-MHz fingers to the ultrasound generated by the 5-MHz generating transducer is shown in figure 6(a). Several peaks at different frequency bands were detected in the middle diagram, labeled A, B, C and D in the figure. Obviously, peak A includes the resonances of the 1-MHz fingers; this includes both the fingers’ resonance with in-phase motion and the resonances of fingers with different phases. The trace corresponding to peak A is shown by figure 6(c); the SNR of the detected signal is so high that the signal can be observed without averaging. B, C and D in the figure are, by c-scan, shown to be different modes of bridges of the transducers instead of fingers’. Similar results for a large transducer with 1-MHz fingers were also obtained. Figure 6(b) shows the dynamic response for a \textit{b} type large transducer with 1-MHz fingers, where the corresponding ultrasound was also generated by the 5-MHz piezoelectric transducer.

It should be emphasized that the ultrasound corresponding to the dynamic response in figure 6(a) was generated by a 5-MHz piezoelectric transducer (figure 5). In this case the amplitude of the generated ultrasound around 1 MHz should be smaller relative to that around 5 MHz due to the dynamic properties of the generating transducer. Despite this, much stronger ultrasonic signals around 1 MHz were detected, as shown by the frequency spectrum in figure 6(a and b); on the contrary, the detected ultrasonic signals around 5 MHz are rather weak. This shows that the fingers’ resonance is a dominant factor in achieving high sensitivity for ultrasound detection; only signals of waves within the transducer’s designed frequency band around its resonances are amplified by the transducer; sounds or noise out of this frequency band of the transducer
cannot cause the resonance of fingers, and therefore are not amplified by the MEMs fingers. This enables the transducer to be particularly noise resistant while its high sensitivity to ultrasound remains. The resonances of bridge separations only widen this frequency band of the transducer with a sensitivity lower than that of the fingers.

However, this dynamic property of the transducer also shows that the designed detection transducer has a narrow bandwidth. This may cause difficult in using of this type of transducer; for any ultrasound with a frequency out of the narrow bandwidth of the transducer, the sensitivity of the transducer will soon decrease to the same level as traditional transducers’.

2.4. Sensitivity measurements
In the experimental configuration shown by figure 5, we used a laser vibrometer to replace the optics in the system, so that the amplitudes at both fingertip and substrate around finger’s root would be measurable for a given pulsed excitation on the piezoelectric generation transducer in the system. The scanned finger’s modes are shown in figure 7 (b, c and d, top) respectively and the measured corresponding finger tip amplitudes are illustrated by figure 7 (b, c and d, middle). However, in this case, we found out that the finger’s root noise level amplitude is nearly immeasurable, as shown by figure 7 (b, c and d, bottom).

A Tektronix AFG 3252 signal generator was used to drive the 5-MHz piezoelectric transducer with a continuous sinusoidal RF signal. The frequency of the sinusoidal signal was set to the measured finger resonance; this enables a good resonance of the finger. In this case, both the amplitudes of finger tip and substrate can be measured. However, it is still difficult to define the actual root amplitude; the root/substrate amplitude is found to vary across the substrate and in the vicinity of each root. Despite this, it is possible to establish a relative relationship between the root/substrate amplitude and the fingertip amplitude. An arbitrary but fixed point was chosen around a root to measure the relative root displacement. The measured results, processed by Fourier transformation, are shown by figure 8 for different fingers. They show

Figure 6. (a) Dynamic response of an a type small transducer with 1-MHz fingers. (b) Typical dynamic response of a b type large transducer with 1-MHz fingers. (c) Typical detected ultrasonic signal shown on an oscilloscope screen.
that the fingertip amplitude has a good linearity with the root/substrate amplitude. Slight nonlinearity for high fingertip amplitudes were also detected; this may be due to the contribution of air damping. This illustrates that the sensitivity/gain of each finger is nearly constant with the excitation amplitude at a given resonant frequency. This is reasonable, because the deflection in each case is far less than the linear range of small deflection defined by elasticity theory[19]; FE methods can be applied to analyze that the maximum strain along the axial direction of a finger—in the extreme test case with the highest tip amplitude—is only in the order of $10^{-5}$; the vibration is indeed in the range that can be described as small deflections. In addition, the ratio between maximum tip displacement and finger length is at order of $10^{-4}$. This shows the slope of each finger in vibration is relatively small and thus geometric nonlinearity caused by deflection can be ignored [20]. In this case from elasticity theory [19], the tip amplitude must be linear with the root excitation amplitude even at the resonance state. At a frequency away from a finger’s resonance, this linear relationship should remain; the sensitivity/gain decreases as the frequency moves away from its resonance, however, it remains constant provided the frequency is fixed. In these cases the finger’s tip amplitude is more sensitive to the frequency, as shown by figure 6.

The slopes of the curves in figure 8 broadly agree with the sensitivity/gain we defined in equation (1). However, we found out that although the linear relationship between input amplitude and output amplitude remains, the slope of each curve strongly depends on the root amplitude measuring location; for example with the 1-MHz finger, the slope varies from about
Figure 8. Sensitivity measurements for different fingers with 1 MHz (top), 2 MHz (middle) and 3 MHz (bottom) respectively, the slope of each curve is the corresponding measured sensitivity for different fingers.

700 to several thousand around the vicinity of the root. The variation in the substrate amplitude is thought to originate from the standing waves in the substrate, the influence of the vibrating finger and from waves, especially surface waves, being radiated from the fingers. Because the substrate amplitude was found to vary across the substrate (especially in the vicinity of the fingers) it was difficult to measure the driving amplitude and therefore difficult to measure the gain. As a result we can only put a lower limit on the gains as $\geq 700$ for the 1-MHz transducer, $\geq 550$ for the 3-MHz transducer and $\geq 60$ for the 5-MHz transducer.

3. Optical MEMs generation transducer

3.1. Geometry and working principle

we present an optically powered MEMs transducer for the generation of narrowband ultrasound with high amplitude/SNR, providing a different solution to the optical shot noise problem for laser ultrasound generation and detection. It is a 3-D elastomechanical micro-structure, a typical MEMs device, consisting of a resonant microdisk, seated on a solid microstem, as shown by figure 9(a). This transducer generates longitudinal waves in a narrow bandwidth with higher amplitude than would be excited with the same optical power without the transducer present. It has high efficiency, compact size and a wide application range by using simple optics with a common pulsed laser source.

When a laser pulse is incident on a microdisk (figure 9(a)), it produces localized temperature differences and stresses which excite the vibrational modes of the entire structure due to its small size. A surface wave with a circular wavefront is actuated first at a laser pulse (see figure 9(b)). As this surface wave propagates towards the edge of the disk, it turns into an antisymmetric...
Figure 9. (a) Schematic design of the geometry of an optical transducer. It is a microdisk with a diameter $d_d$ and a thickness $h$, seated on a microstem with a diameter $d_s$ and a length $h_s$. As a laser pulse is incident on the center of the disk, a resonant flap motion of the disk is activated, coupling a longitudinal wave propagating along the axis of the stem. (b) A surface wave is actuated first at the disk center at a laser pulse. (c) The surface wave turns into an antisymmetric Lamb wave as it passes the flange root of the disk. (d) Reflections of the Lamb wave between the disk edge and root turn the Lamb wave into a flap motion of the disk.

Figure 10. (e) Geometry of an optical generation transducer of an FE model. (f) The ultrasonic waves predicted by FE simulation from the transducer shown by (e) at top right corner of the figure, and by a laser pulse. C, B and A show the generated surface wave, shear wave and longitudinal wave respectively.
Lamb wave at the disk root (see figure 9(c)) because of the small thickness of the disk. After this, reflections of the Lamb wave between the disk edge and the disk root start because of the small step length $\Delta d$ and soon turn the Lamb wave into a resonant flap motion of the disk (figure 9(d)).

The disk structure is a resonator and the resonance determines the frequency of the transducer. The modes activated by a laser pulse tend to be dominated by one of the natural resonances of the disk, referred to as the main frequency/mode of the transducer; this mode tunes the vibration of the disk. Usually it is the first resonance that is dominantly actuated if the disk is 2-D and axisymmetric. Depending on the parameter $\frac{\Delta d}{h}$, the material and the optical actuation, more modes—higher or lower than the main mode of the transducer—may be actuated at the same time, in particular for the case where the transducer is nonaxisymmetric. It is necessary to point out that although theoretically a transducer can be simplified to be 2-D axisymmetric, an actual transducer is usually nonaxisymmetric because of material anisotropy, fabrication errors or the optical alignment; the actual main frequency can be a higher order resonance. For an axisymmetric 2-D disk with a suitable $\frac{\Delta d}{h}$, and the laser pulse being incident on the disk center, the actuated modes are dominated by the first resonance of the disk, resulting in a nearly sinusoidal resonant flap motion of the disk. Because the disk is elastically supported by the solid stem, this resonant flap motion couples a surface wave traveling along the surface of the stem. A surface wave consists of a transverse wave and a longitudinal wave [21]. Due to the structural axisymmetry, the phase of the transverse wave is axisymmetric with respect to the cross section of the stem. Thus, the coupled transverse wave is canceled out because of the small diameter of the stem. However, the coupled longitudinal wave is in-phase around the stem cross section. Therefore, the coupling of the disk resonant flap vibration leaves an enhanced longitudinal wave, traveling along the axis of the stem, with a bandwidth the same as that of the disk resonant motion. Because the bandwidth is defined by the resonant motion of the disk, it should be narrower than normal laser generation of ultrasound reported in the literature [10, 11, 12, 13].

From this working principle, two conditions are important for a successful transducer design: only one mode is dominantly actuated and the phase of the mode should be the same around the circumference of the disk. The first condition ensures the generated wave is narrowband; the second enables most of the kinetic energy induced by the absorbed optical energy being tuned into this narrowband wave. Therefore, it is a key step to design a disk resonator, by which, for a given laser pulse, only one mode is dominantly actuated while other modes should be minimized. In a case where the disk of the transducer is not 2-D, or the transducer is not axisymmetric, the resonant mode may be nonaxisymmetric with a phase changeable around the disk circumference. In this case the coupled transverse wave cannot be completely canceled while the longitudinal wave may be partially canceled. This reduces the efficiency and decreases the SNR of the ultrasound system, or widens the corresponding bandwidth; as a consequence, the amplitude of the generated ultrasound is reduced. Figure 10 shows the FE simulated ultrasonic waves generated by a microdisk MEMS transducer.

3.2. Design and fabrication of the transducer
The purpose of the design process is to define the optimum geometry of a transducer for a required frequency to achieve the ultrasound with the highest amplitude. The geometries of the designed MEMs transducers are shown by Table 1 with frequencies of 1, 2 and 3 MHz respectively. The 1-MHz transducers were designed as being optimal and the 2- and 3-MHz transducers were designed for comparison. As a typical two-mask-level MEMs device, the transducer design is strongly influenced by the fabrication process. The transducers were fabricated by the standard SOIMUMPs process at MEMSCAP. SOI wafer was used once again as the basic material for the transducer design and fabrication. Therefore, the disk thickness
Table 1. Frequencies and dimensions of designed MEMs transducers

| f (MHz) | \(d_d(\mu m)\) | \(d_s(\mu m)\) | \(h(\mu m)\) | \(h_s(\mu m)\) |
|---|---|---|---|---|
| 1 | 412 | 100 | 1 | 462 |
| 2 | 310 | 100 | 200 | 310 |
| 3 | 272 | 100 | 200 | 372 |

is \(h = 25\mu m\) for all generation transducers. Figure 11(a) shows the top view of the designed transducers. The 3-D structure for a 3-MHz transducer is shown by figure 11(b). As can be seen from the image the fabricated stem is not a solid cylinder as shown by figure 9(a) but a truncated cone due to the restrictions of the design rules of the fabrication process. In this case the stem diameter means the diameter of cross-section of the stem against the lower surface of the disk. In addition to this, four spokes are used to support the transducer; each spoke is only connected to the stem at the bottom location while the upper part of each spoke and the disk are completely free from each other.

Two deep reactive ion etching processes were used to fabricate the transducer. Details of the fabrication process can be referred to at the website of MEMSCAP. Figs. 11(c–f) are images of fabricated transducers under a microscope, where (c) shows the top view of two 1-MHz transducers with \(d_s=100\) and 150\(\mu m\) and (e) shows the top view of two 3-MHz transducers with the same \(d_s\). Figs. 11(d) and (f) demonstrate the corresponding back side images of the transducers, where the blurred part in each photo is the image of the disk for each transducer viewed from the back side of the wafer.

3.3. Experimental study of the MEMs generation transducers

In order to check if the designed and fabricated transducers can be applied to optically generate ultrasound with a high amplitude as expected, a system was configured, as shown in figure 11(g), to conduct experimental studies with these fabricated transducers. The optical transducer sample is attached to the surface of a metal block with a given thickness. The metal block is bonded to the surface of a piezoelectric transducer. As a laser pulse is incident on the disk of a transducer on the sample (figure 11(g, top)), the generated ultrasound travels through the metal block and can be sensed by the piezoelectric transducer (figure 11(g, bottom)). We used again the 5-MHz Videoscan piezoelectric transducer. Figure 12(h)∼(k) illustrate the detected ultrasound by the test system with the piezoelectric detection transducer, and aluminum blocks with different thicknesses of 10 and 15mm respectively.

Figure 12(h) shows the generated longitudinal wave and the corresponding Fourier transformation by a 1-MHz MEMs optical transducer; it has a narrow bandwidth, centered at 0.89 MHz with a high amplitude at the frequency, and with a 15 mm aluminum metal block. Similarly figure 12(i) shows the generated strong signal around 1.98 MHz and the corresponding Fourier transformation for a 2-MHz transducer, and with a 15 mm aluminum metal block. For a 3-MHz transducer with a 10-mm aluminum block, the generated longitudinal wave is shown by figure 12(j).

In order to show the high efficiency of this optical transducer, a comparison between the
Figure 11. (a) Image of top view of the designed 1-MHz (left), 2-MHz (middle) and 3-MHz (right) transducers with stem diameters of 100, 150 and 200 µm respectively. (b) 3-D structure of a 3-MHz transducer. (c) and (d) Front and back images of the 1-MHz transducers with different stem diameters under a microscope. (e) and (f) Similar images of 3-MHz transducers. (g) Experimental configuration.

Figure 12. (h)∼(k) Ultrasound measured by test system (figure 11(g)) and produced by the fabricated MEMs generation transducers at laser pulses.
transducer generation and the normal thermoelastic generation has been shown by figure 12(h) and figure 12(k). The diagram (k) shows the ultrasound by normal thermoelastic generation with the same optics using the substrate surface away from any structure on the transducer sample. It can be seen that amplitude of the broadband ultrasound by normal thermoelastic generation is only at the noise level of the narrowband ultrasound generated by the MEMs transducer; the amplitude of the generated narrowband ultrasound is at least 5 times higher than that of the normal thermoelastic generation (figures (h) and (k) are on the same scale). More important is that the SNR of the narrowband ultrasound is much higher than that of the broadband ultrasound generated. It is an interesting fact that the amplitude achieved by the MEMs transducer was difficult to reach by normal optical generation, even with the input optical power in the ablation regime. This is an advantage of this optical transducer over a simple absorption layer.

For the resonant flap motion of a disk, it is not necessary for the laser light to be well focused; a laser spot matching the disk radial dimension can increase the laser power while the power density still remains within thermoelastic regime. Thus, pulsed light from a laser with relatively higher power can be applied to this transducer. A hopeful improvement of the transducer is to combine with the technique presented in [7] with a highly absorbing layer deposited onto the disk surface of the MEMs transducer for a laser with less power. For high frequency narrow band ultrasound, a finer disk array transducer perhaps can be designed.

4. Future work
4.1. Optical MEMs shear wave transducer
Some possible work in the near future is shown in figures 13 and 14. The first work that can be done is to design an optical MEMs narrowband shear wave generation transducer, as shown by figure 13(a∼c). (a) shows the working principle of the MEMs structure. It is a vertically fabricated cantilever on a solid material surface. When a laser pulse is incident upon one side of the vertical finger, its first resonance would be activated. The connection between the finger and the bulk material underneath is elastic, so that the motion of the finger root can be decomposed into a rotation and a shear motion along the solid surface at the first resonant motion of the finger. The shear motion can produce a shear wave propagating into the material underneath, while rotation around the root can be equivalent to two vertical displacements, along the two-sides of the finger with opposite direction and with the same amplitude. Because these two motions are close to each other, they generate nearly nothing for any location far away from the root. This shows a vertical cantilever MEMs structure can be used as a shear wave generation

Figure 13. Possible future work on optical MEMs detection and generation transducers. (a) Working principle of a narrowband shear wave transducer. (b) FE predicted shear waves generated by a vertical cantilever shear wave transducer at a laser pulse. (c) manufacturable MEMs structure for an optical shear wave generation transducer.
transducer. Figure 13(b) shows FE predicted shear wave generated by such a transducer at a laser pulse. However, this vertical cantilever structure is difficult to manufacture, we present an improved equivalent MEMs structure, as shown by figure 13(c); it functions as a vertical cantilever and is possible to be manufactured by surface micromachining technology.

4.2. Improvement of detection transducer

Although the designed optical MEMs detection transducer has a much higher sensitivity to ultrasound than traditional ones [5], it has a narrow bandwidth; for any ultrasound with a frequency out of this narrow bandwidth, the sensitivity of the transducer will soon decrease to the same level as traditional ones. In order to increase the bandwidth of the transducer, a new MEMs structure is presented as shown by figure 14(d), with changeable finger lengths. Because the length of each finger is different, the first resonance of each finger is also different, thus ultrasound with different frequency will select different finger to resonate. Due to the actual damping of each finger, if one finger is in resonance, the fingers adjacent to it will also have relatively high amplitude provided the change rate of finger length is not too high. In actual design, it should make sure that for ultrasound with any frequency within the bandwidth, at least there should be more than three fingers in motion and have relatively high amplitudes to enable the transducer work[5]. Figure 14(e) shows FE predicted bandwidth of the new MEMs structure.

4.3. A possible simple but efficient optical laser generation and detection system

Our aim is to set up a simple but efficient optical laser generation and detection system, as shown in figure 14(f) as an example. Upon a metal block, at one side an optical generation transducer is attached, and on the opposite side, an optical detection transducer is amounted. We hope the optically generated ultrasound at a laser pulse, propagating through the metal block with given dimensions, can still be detected by the optical detection transducer on the other side. Thickness of the metal block will be an important assessment parameter to the system. The key factor to make sure the system works is the bandwidth of the detection transducer. It should be sufficiently wide to include the frequency of the generated ultrasound within it and to ensure more than three fingers of the detection transducer are activated at the same time.

5. Conclusions

- Microcantilever optical ultrasound detection transducers were successfully designed, fabricated and used to detect ultrasonic waves with high sensitivity. The sensitivity of
the transducer is \(~\sim\) 1–3 orders of magnitude higher than conventional CHOTs or other optical detection techniques. The sensitivity is \(\geq 700\) for the designed 1-MHz transducer, \(\geq 550\) for the 3-MHz transducer and \(\geq 60\) for the 5-MHz transducer. The transducer is highly noise resistant, and geometrically compact. No wiring or power connections are required, lending the transducers themselves to remote non contact applications and to those in hostile environments. These transducers are also inexpensive even in prototype numbers; the cost of per transducer was less than $10. However, the transducer has a narrow bandwidth.

- Optical MEMs generation transducers were designed and fabricated. FE simulation and experimental study have shown that these transducers can be applied to optically generate narrowband ultrasound—surface wave, shear wave and longitudinal wave—with high efficiency, high amplitude/SNR and narrow bandwidth; compared with normal thermoelastic generation, ultrasound with at least 5 times higher amplitude can be achieved by a suitably designed optical transducer. Only a simple optical arrangement is required to use this transducer.

- It is possible to design an optical MEMs shear wave generation transducer, and to design an optical detection transducer with a suitable bandwidth in the near future. Our aim is to set up a simple but efficient optical laser generation and detection system.

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