Study of a high efficiency optical MEMS transducer for the generation of narrowband laser ultrasound

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Abstract. In this paper we demonstrate an optically powered ultrasonic transducer. It has a high efficiency and was designed and fabricated using MEMS (microelectromechanical system) techniques. It can generate narrowband ultrasound from broadband laser excitation. It is a simple two-mask-level MEMS device with a micro-disc seated on a micro-stem. As a laser pulse is incident on the disc centre, the disc is excited into a 'flapping' motion because of the thermomechanical interaction between the absorbing and non-absorbing parts of the disc. This flapping motion is dominated by one of the resonances of the disc, coupling a narrowband longitudinal bulk wave propagating along the axis of the micro-stem into the sample. Experiments with these transducers have shown that narrowband ultrasonic waves with a high SNR (signal to noise ratio) were generated successfully. The device is simple to excite optically and generates higher amplitudes than by normal thermoelastic generation. No physical contact is required to excite the transducer, making it suitable for remote non-contact ultrasonic applications.

1. Introduction.
Narrowband laser ultrasound is suitable for applications in industry [1], space technology [2, 3], medical treatment [4–7] and NDT [8, 9]. However, techniques to generate narrowband laser ultrasound have been limited [1, 10]. Other methods to optically generate narrowband ultrasound are those using complex optical arrays [11, 12] and special techniques [13, 14]. In this paper, an optical narrowband ultrasound generation transducer with high efficiency and a high SNR is presented. Fundamentally, it is a 3-D elastomechanical structure, a typical MEMS device, consisting of a micro-disc with diameter \( d \) and thickness \( h \), seated on a solid micro-stem with diameter \( d_s \) and length \( l_s \), as shown by figure 1(a). Compared with other narrowband ultrasonic devices [10], transducer systems [14] or optical arrays [11, 12] in literature, the fundamental characteristics of this optical MEMS transducer are its small dimensions, high efficiency and wide application range by using a single general laser source with simple optical arrangements. In addition to these, it was potentially economic; it can be considered as to be disposable, and to be massless for most engineering applications.

2. Working principle
In normal thermoelastic excitation where a laser pulse being incident on the surface of a sample the generated ultrasound is broadband [15-17]. When a laser pulse is incident on the micro-disc of the transducer (figure 1(a)), it produces localised temperature differences and stresses which excite the vibrational modes of the structure. In the case where laser light was well focused, a surface wave with a circular wavefront is actuated first in the centre of the disc (see figure 1(b) by FE (finite element)). As this surface wave propagates towards the edge of the disc, it mainly turns into a Lamb wave with a circular wavefront at the root (see figure 1(c)) because of the small thickness of the disc. After this, reflections of the Lamb wave start between the disc edge and the root because the step length \( \Delta d \) of the flange is small, and soon turn the Lamb wave into a flapping motion of the flange part of the disc, as shown by part (d) of the figure. If the laser light is not well focused, the light spot can be close to or larger than the stem diameter of the transducer. In this case, the Lamb wave may be directly generated within the flange part of the disc. The micro-disc structure plays an important modulation part in the actuated disc motion frequency; the frequency of the laser pulse actuated disc motion always tends to be as close as possible to the first resonance of a 2-D axisymmetric micro-disc; higher modes may be slightly actuated, depending on the parameter of \( \Delta d/h \) (see figure 1), pulse duration and stem diameter as well. Because the disc is elastically supported by the solid stem, this flapping motion of the disc couples an elastic surface wave travelling along the surface of the solid
Figure 1. (a) Schematic design of the geometry of an optical generation transducer. It is a micro-disc seated on a micro-stem. As a laser pulse is incident on the centre of the micro-disc, a flapping motion of the disc flange is actuated with a frequency defined by one of the resonances of the disc, and couples a longitudinal bulk wave propagating along the axis of the micro-stem. (b) A surface wave is actuated first at the disc centre by a laser pulse, simulated by FE. (c) As the actuated surface wave travels from the disc centre towards the edge, it turns into an antisymmetric Lamb wave as it passes the flange root of the disc. (d) A disc flapping motion actuated by a laser pulse.

Due to the axisymmetry of the micro-stem, the phase of the transverse wave is axisymmetric with respect to the cross section of the stem, resulting in a cancellation of the transverse wave due to the small diameter of the stem. However, the coupled longitudinal bulk wave components are in-phase around the micro-stem cross section. Therefore, the elastic coupling of the free disc flapping vibration generates an enhanced longitudinal bulk wave, travelling along the axis of the stem, with a frequency the same as that of the flapping motion of the disc; it is a narrowband longitudinal bulk wave with a frequency defined by the first resonance of the disc; components with higher frequencies may be included, depending on the transducer geometry, materials and the laser pulse duration; however, the amplitude corresponding the first resonance of the micro-disc must be dominant.

Figure 2. Geometry design of the narrowband optical MEMS generation transducer. (a) Image of top view of the designed transducers with 1 MHz (left), 2 MHz (middle) and 3 MHz (right). (b) Three dimensional structure of a designed 3-MHz transducer. (c) and (d) Microscope images of the front and back of fabricated 1-MHz transducers with different stem diameters. (e) and (f) Similar microscope images of 3-MHz transducers.

3. Design and fabrication

The basic task of designing the MEMS generation transducer is to define the geometry of the transducer over the required frequency parameter. The basic dimensions of the micro-disc of a transducer can be defined by using FE eigen analysis. The dimensions of the designed transducers are shown in Table I. Figure 2(a) shows the top view of the designed transducers. The left three in diagram (a) are the transducers with a frequency around 1 MHz, and the diameters of the stems are $d_s=100$, 150 and 200 μm respectively. The middle three are with a frequency around 2 MHz and the right three are 3-MHz transducers. The 3-D structure for a 3-MHz transducer is shown in figure 2(b). Two deep reactive ion etching processes were used to fabricate the transducer. Detailed fabrication process can be referred to at the website of MEMSCAP (refer to http://www.Memscap.com). Figures 2(c)∼(f) show images of fabricated transducers under a microscope, where figure (c) shows the top view of two 1-MHz transducers and diagram (e) shows the top view images of two 3-MHz transducers. Figs. 2(d) and (f) are the backside images of the same transducers.

4. Experimental study

In order to check if the designed MEMS transducers can be used to generate the ultrasound as expected, two experimental systems were configured, as shown in figure 3. Figure 3(a) shows a c-scan system which uses a laser vibrometer to measure out of plane motion. The head of the vibrometer was mounted on an x-y scan
Table 1. Frequencies and dimensions of the designed transducers

| f (MHz) | d (μm) | d (μm) | h (μm) | h (μm) |
|---------|--------|--------|--------|--------|
| 1       | 412    | 100    | 25     | 401    |
| 1       | 462    | 150    | 25     | 401    |
| 1       | 512    | 200    | 25     | 401    |
| 2       | 310    | 100    | 25     | 401    |
| 2       | 360    | 150    | 25     | 401    |
| 2       | 410    | 200    | 25     | 401    |
| 3       | 272    | 100    | 25     | 401    |
| 3       | 322    | 150    | 25     | 401    |
| 3       | 372    | 200    | 25     | 401    |

Stage. A sample of MEMS transducers was mounted on a stiff frame on the test table. Light pulses produced by a Q-switched Nd:YAG laser were used to excite the transducer. Using the laser vibrometer, the actuated motions of both the disc and the stem bottom surface can be scanned. In this configuration, the optical transducer was elastically supported by the four spokes (refer to figure 2(b)), and the stem bottom surface was mechanically free, as shown by right part of the diagram (a) of figure 3. In the configuration shown in figure 3(b), the transducer sample was attached to the surface of a carrier with thickness hc. The carrier was bonded to the surface of a piezoelectric transducer. As a laser pulse is incident on the disc of a transducer on the sample, the generated ultrasonic wave travels through the carrier and can be sensed by the piezoelectric transducer. We used a 5-MHz ‘Olympus V609-SB 5.0/0.5 Videoscan’ piezoelectric transducer with a bandwidth of about 110%. In this configuration, the stem of the optical transducer was not only supported by the four spokes (refer to figure 2(b)), but also bonded to the surface of the carrier, so that the bottom surface of the stem was nearly fixed, as shown by the right part of the diagram (b) of figure 3.

Figure 3. (a)(left) Experimental configuration for acquiring a c-scan using a laser vibrometer. The laser light from the vibrometer head scans the bottom part of the transducer point by point. In this configuration the bottom surface of the transducer is mechanically free (a, right) and the transducer is elastically supported by the four spokes. (b)(left) Configuration directly measuring the optically excited ultrasonic signal by using a piezoelectric transducer. The optical transducer was attached to the piezoelectric transducer surface via an aluminium carrier with thickness of hc. In this configuration the bottom surface of the micro-stem of the transducer and the bottom surface of each spoke are bonded to the carrier, so that the bottom surface of the stem was nearly fixed (b,right).

Figure 4 consists of several c-scans, which show modal shape images for different transducers at different resonances by using the experimental system illustrated by figure 3(a). Figure 5(E) shows the ultrasonic signals detected at the stem bottom surfaces. Figure 5(F) illustrates the detected ultrasonic signals by the test system shown in figure 3(b) with the piezoelectric detecting transducer and aluminium carriers with different thicknesses of 10 and 15 mm respectively. It can be seen from figure 4 that a flapping motion of the annular part of the disc for each transducer was successfully excited by the incident laser pulse. Figure 4(a) and (b) show the modal shape at resonance of 0.89 MHz for a 1-MHz transducer; image (a) shows the amplitude of displacement out of the disc plane and (b) illustrates the corresponding phase. As it can be seen that the modal shape of the disc at 0.89 MHz resonance was almost axisymmetric. Compared with the amplitude of the flange flapping motion, the displacement of the bottom surface of the stem was much less. However, both the phase and amplitude of the surface displacement are nearly constant, as shown by diagrams (b) and (c),
suggesting a longitudinal wave being generated. It can be shown that as the frequency is slightly different, for instance, from 0.89 MHz to 0.98 MHz, the corresponding phase and amplitude were soon below the noise level. This indicates the generated ultrasonic longitudinal bulk wave from the stem bottom surface has a narrow bandwidth, centred at 0.89 MHz. The waves of the stem bottom surface are averaged and analysed.

Figure 4. (a) Amplitude of a 1-MHz transducer with a 100 μm stem diameter at resonance of 0.89 MHz actuated by a laser pulse, the corresponding phase (b) and the amplitude distribution at the bottom surface of the micro-stem (c). (d) Amplitude of a 2-MHz transducer with a 200 μm stem diameter at resonance of 1.98 MHz, the corresponding phase (e) and the amplitude of the micro-stem surface (f). (g) Scanned amplitude of a 3-MHz transducer with a 150 μm stem diameter at 3.1 MHz, its corresponding phase (h) and the scanned amplitude of the stem bottom surface (i). All images are of an area 400×400 μm.

FIG. 5: Ultrasound generated by the fabricated transducers, detected by the first and second experimental configurations. (E) The left diagrams show the average displacement at stem bottom surface and the right diagrams show the corresponding Fourier transformations for a 1-MHz transducer with a stem diameter of 100 μm (E, top), a 2-MHz transducer with a 200 μm diameter stem (E, middle) and a 3-MHz transducer with a 150 μm diameter stem (E, bottom) respectively. (F) The left diagrams show the detected traces and the right diagrams show the corresponding Fourier transformations for the 1-MHz transducer with an aluminium carrier with thickness of 15 mm (F, a), the 2-MHz transducer with the same carrier (F, b), and the 3-MHz transducer with a 10 mm carrier (F, c). Diagram (F, d) shows the ultrasound excited by normal thermoelastic generation with same actuation conditions as in diagram (F, a) of the figure.

by Fourier transformation with a result shown by figure 5(E, top). As it can be seen that the generated ultrasonic signal around 0.89 MHz, labeled A, was the strongest while there are some other signals with different frequencies marked by B, C, D and E respectively. These are assumed as the signals coupled from the actuated higher modes of the transducer. All modal shapes corresponding to figure 5(E, top) marked by B, C, D and E were obtained and shown to be 3-D. However, these ultrasonic signals with frequencies higher than the designed 1 MHz frequency are not obviously detected by using the detection system shown by figure 3(b) with the 5-MHz piezoelectric transducer and an aluminium carrier with a thickness of h =15 mm, as shown by figure 5(F, a); a strong narrowband signal around 0.89 MHz was detected once again while other signals with higher frequencies, as shown in figure 5(E, top), are nearly zero. One reason for this was that the signals with higher frequencies probably completely decay whilst propagating over a distance of...
15mm due to mechanical damping of the carrier. Another possible reason was that the mechanical boundary conditions are different for the transducer when the experimental configurations in Figs. 3(a) and (b) are applied respectively, as shown by the right part of the figure. It is possible that the higher modes are not actuated in the second configuration because of the enhanced support stiffness of the transducer. A similar discussion can be had for the 2-MHz transducer with a 200 μm stem diameter; the scanned images were shown in Figs. 4(d), (e) and (f) respectively, the averaged ultrasonic signal at the bottom surface of the stem is shown in figure 5(E, middle) and the the signal detected by the piezoelectric transducer is shown by figure 5(F, b). For the 3-MHz transducer with a 150 μm diameter stem, its modal shape at resonance 3.1 MHz is shown in figure 4(g) and (h), and the generated longitudinal bulk wave is shown by (h) and (i). The corresponding scanned ultrasound and the ultrasound measured by the piezoelectric transducer are shown in figure 5(E, bottom) and (F, c) respectively. Note that by the dimensions (see Table 1) and from a mechanics point of view, only the disc of the 1-MHz transducer can be approximately considered as being 2-D, while the discs of 2- and 3-MHz transducers are more likely to be 3-D. Comparing the detected ultrasound shown in figure 5, the wave generated by the 1-MHz transducer has the most narrow bandwidth and the highest SNR; the waves generated by the 2-MHz transducer were in the middle and the waves generated by the 3-MHz transducer were the worst. The corresponding parameter of Δd/h is 6.2, 4.2 and 3.4 respectively. This shows it is important to design a 2-D disc for the optical MEMS transducer to generate narrowband laser ultrasound with high SNR. As a comparison, figure 5(F, d) shows the ultrasonic signal by normal thermoelastic generation of the same laser pulse actuation as in diagram (F, a) of the figure from the substrate beside the MEMS transducer. Obviously, the amplitude of the wave generated by the MEMS transducer is at least 5 times higher than that generated by the normal thermoelastic generation, showing the MEMS transducer having a much higher efficiency than normal thermoelastic generation.

5 Conclusions.
In this paper we have demonstrated an optically activated transducer for the generation of narrowband laser ultrasound. Optical MEMS generation transducers were designed and fabricated. Experimental studies have shown that these transducers can be applied to optically generate narrowband longitudinal wave ultrasound with high efficiency and high SNR. Optical alignment is not important for the generation of ultrasound. In order to generate narrowband ultrasound with high SNR it is important to design the micro-disc to be 2-D. The transducers are very small and capable of generating longitudinal waves with amplitudes at least five time higher than that of normal thermoelastic laser generation using the same input optical power.

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