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Endoscopic system for *in situ* ultrasonic inspection of aero-engines using optically excited ultrasonic transducers

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Abstract

CHeap Optical Transducers (CHOTs) are a non-contact, wireless, couplant-free alternative to the traditional piezoelectric transducers and can be used for ultrasonic inspection. Because they are cheap and very small, they can be used in large numbers and in different ways to normal ultrasonic probes. For example, they could be mounted permanently on the component for easy repeatable measurements or considered as disposables: use once and throw away. CHOTs are structures attached to the surface of the test component that are optically excited using a simple laser set-up to either generate or detect ultrasound. The use of CHOTs enables testing of components inaccessible by other techniques and potentially enabling on-site and in-service ultrasonic testing currently unavailable to the industry. An example case study of CHOTs for *in situ* inspection of aero-engines, without dismantling them will be presented. An endoscopic system for CHOTs excitation has been developed which uses optical fibres for generating and detecting the ultrasonic signal. The design and construction of the portable system will be presented as well as the various methods for fabricating, attaching and "reading" the CHOTs.

1. Introduction

Ultrasound is a powerful technique that allows the user to test, non-destructively, optically opaque materials. During ultrasonic testing, the ultrasound travels inside the component or along its surface and the detection of this signal provides information about the component's properties, thickness or the presence of defects. The generation and detection of ultrasound is usually performed by contact devices such as piezoelectric transducers which need couplant (usually water), have a certain size, use wires and most of the times need to be in close proximity to the component. CHOTs (CHeap Optical Transducers) offer solutions to these limitations. They are ultrasonic transducers that are excited optically by means of lasers and can be used to enhance, control and detect ultrasound. They are very small devices of a few millimetres length and nanometres height, which are activated remotely and wirelessly because they use light. Due to these advantages and the fact that they are cheap and can be used in large numbers, used as disposables or left permanently mounted on the component, CHOTs offer an effective alternative to piezoelectric transducers where size restrictions are severe or, access is difficult or the environment is hostile, potentially enabling on-site and in-service ultrasonic testing currently unavailable to the industry.

We have previously demonstrated the use of CHOTs for generation and detection of surface [(1,2,3)] and longitudinal [(4)] acoustic waves. In the present article an endoscopic system for CHOTs excitation is presented which uses optical fibres for generating and detecting the ultrasonic signal. It is part of a case study for the endoscopic use of CHOTs, for *in situ* inspection of aero-engines, without dismantling them.

2. Background: How do CHOTs generate and detect ultrasound using light?

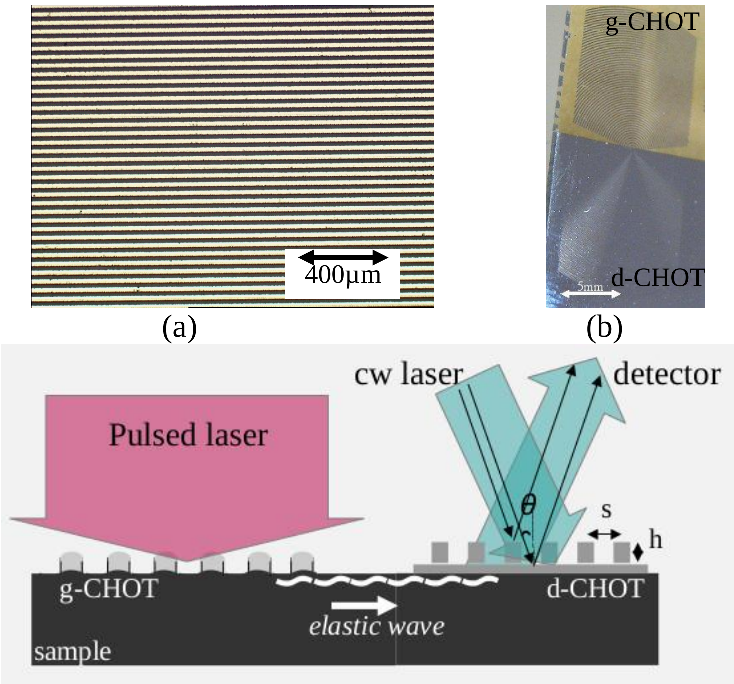
The principle of operation of CHOTs is based on laser ultrasonics [(5)]. In conventional laser ultrasonics, the pulsed laser light is absorbed directly by the irradiated component which heats up and expands rapidly, at times that are compared to the rise time of the laser pulse (nanoseconds duration) [(6)]. This fast thermo-elastic expansion is the source of the generated ultrasonic wave. The wave then travels through the component and is detected optically, usually by some type of laser interferometer [(7)]. There are certain advantages in this configuration: the surface of the component remains un-altered and scanning is possible. However there are certain disadvantages: the generation and the detection system rely on complicated optical setups and a pre-determined stand-off distance. Interferometers in particular are very difficult to operate in industrial settings, where environmental vibrations are very difficult to isolate.

CHOTs offer to become a bridge between the world of transducers and laser ultrasonics. They are simple 2-D patterns attached onto the surface of the component and they act as optically excited transducers. The advantages they bring is that now the pattern does all the hard work for generation and detection of ultrasound, requiring only collimated light for illumination, eliminating the need of complicated optical setups and alignment. In addition, regarding the detection, as the CHOT’s features are miniature interferometric elements with both the “reference” and the “signal” parts on the tested component, it is very resilient to environmental vibrations.

CHOTs can be split into two types: A transducer that generates ultrasound by using light (g-CHOT) and a transducer that detects ultrasonic signal by translating it into optical information (d-CHOT).

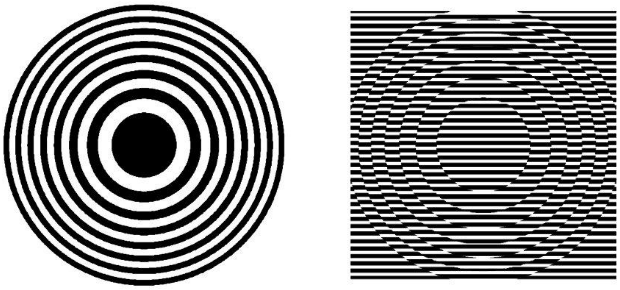
2.1 CHOT for generation of ultrasound (g-CHOT)

The pattern of the g-CHOT creates an absorption contrast on the surface of the component: it creates areas that absorb and areas that reflect (or absorb less) the incident laser light. In other words, the g-CHOT controls the spatial distribution of light on the component and structures the thermo-elastic generation source. In this way the g-CHOT may actively enhance the directivity, the wavemode and the frequency content of the desired ultrasonic signal that is generated. We have developed g-CHOTs for longitudinal and surface acoustic waves (SAWs) and examples of their patterns can be seen in figures 1 and 2. In the case of the CHOTs for SAWs, the g-CHOT sets up an ultrasonic source comprised by an array of line sources with spacing tuned to the wavelength of the ultrasonic wave we wish to enhance and subsequently controls the generated ultrasonic frequency (figure 1). The g-CHOT pattern for the generation of focused longitudinal waves is based on Fresnel zone plate theory, which gives the relation between the ultrasonic wavelength we wish to excite, the ultrasonic focal length and the radii of the Fresnel zones [8] (figure 2(a)).



(c)

Figure 1. CHOTs for generation and detection of SAWs. (a) Photo of a g-CHOT for generation of 80MHz SAWs on glass. The design is the same both for g-CHOT and d-CHOT. However, the black/white areas correspond to areas with absorption deference for the g-CHOT and height difference for the d-CHOT. (b) Photo of a pair of CHOTs for generation and detection of 20MHz focused SAWs on glass. (c) Schematic cross section of the sample showing CHOTs for generation and detection of SAWs.



(a) (b)

Figure 2. CHOTs for focused longitudinal waves. Black/white areas correspond to areas with absorption difference for the g-CHOT (a) and height difference for the d-CHOT (b).

2.2 CHOT for detection of ultrasound (d-CHOT)

The pattern of the d-CHOT is designed to reflect light and is composed of areas with height difference (steps) of a few tens of nanometers. The d-CHOT is a diffraction grating with geometric characteristics matching the ultrasonic wave we wish to detect and height tailored to the optical wavelength illuminating it. The d-CHOT sets up a diffraction pattern for the reflected light and the propagating ultrasonic wave modulates the height of the grating characteristics, causing a re-distribution of the energy among the diffracted orders and a modulation in the orders' intensity. This modulation is directly related to the propagating ultrasonic wave and by isolating an appropriate diffraction order and recording its intensity, the ultrasonic signal is detected. Examples of d-CHOT patterns for detection of SAWs and longitudinal waves are shown in figures 1 and 2.

The d-CHOT for SAWs is a phase grating with pitch equal to the ultrasonic wavelength we wish to detect and step height (h) chosen so that light reflected from the steps has phase difference ($\Delta\phi$) equal to 1/4 of the optical wavelength compared to light reflected from the surface of the sample. The propagating SAW modulates the height of d-CHOT steps, changing the phase grating characteristics and causing a re-distribution of the energy among the diffraction orders [(1)] (figure 1(c)).

The d-CHOT pattern for detection of focused longitudinal waves, is a phase grating superimposed on the Fresnel zone plate (figure 2(b)). Where the two patterns intercept, there is a 90^o phase jump. In effect, there are two phase gratings with exactly the same pitch and step characteristics but with 90^o phase difference. What is modulated here is not the height of the adjacent steps but the relative distance of the two phase gratings from the detector, due to the presence of the incoming longitudinal wave. This modulation causes the interference between the two gratings to modulate as well and it is this modulation that is detected by isolating one of the diffraction orders [(4)].

3. Experimental setup: The endoscopic CHOTs pulser

In order to excite the CHOTs, an endoscopic CHOTs pulser was developed, analogous to the ultrasonic pulsers that excite traditional piezoelectric transducer. The pulser is comprised by the generation laser, the detection laser and the detection system (figure 3). Both lasers are fibre coupled to deliver light at the desired place. Light reflected from the d-CHOT is collected from a third fibre and directed at the photo-detector located inside the CHOTs pulser.

3.1 Endoscopic ultrasonic generation

The generation laser is a Nd:YAG pulsed laser with pulse rise time of 8ns and 1064nm wavelength. Its repetition rate is 1KHz and the average power 650mW. The laser is fibre coupled with a Thorlabs multi-mode fibre. The average power at the end of the fibre is 480mW (approx. 75% coupling efficiency). The laser light is collimated to 5mm diam. spot size at the component side using a single lens.

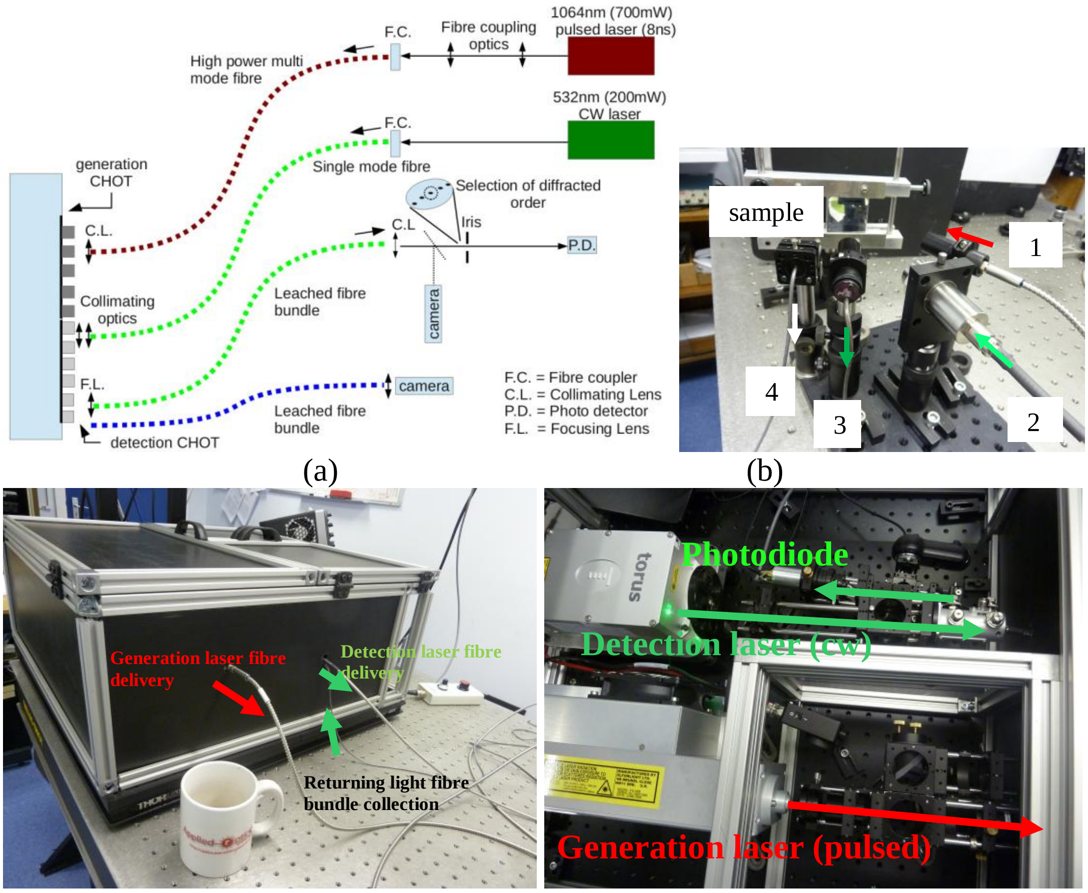


Figure 3. (a) Schematic of the CHOTs pulser. (b) Photo of the light delivery and collection fibre system. 1=Generation laser fibre, 2= Detection laser delivery fibre, 3= Detection light collecting fibre bundle, 4= visual image fibre bundle. c) Photo of the portable CHOTs pulser. (d) Inside the CHOTs pulser.

3.2 Endoscopic ultrasonic detection

The detection laser is a cw frequency doubled Nd:YAG, emitting at 532nm wavelength, with average power 200mW. The laser is fibre coupled to a Qioptiq single mode fibre.

The average power at the end of the fibre is 100mW (approx. 50% coupling efficiency). The laser light is collimated to a 5mm diam. spot size at the component side and after illuminating the d-CHOT, the reflected light is collected by a SCOTT leached fibre bundle (1.45mm quality area diam.) via a lens and then directed back to the pulser, where another lens collimates the light once more and images the diffracted orders onto an iris. The appropriate diffraction order is then isolated and directed onto a photo-diode which detects the modulation in its intensity due to the presence of the ultrasonic wave. In this way, the relatively complex task of separating and selecting the diffraction orders is done inside the CHOTs pulser where there are more relaxed access restrictions.

Just before the iris, a small amount of the returning light is guided towards a camera to facilitate the selection of the suitable diffraction order by the iris. Finally another fibre bundle is located in front of the illuminated component and connected to another camera, providing an image of the surface of the component and guiding the alignment between the fibres and the CHOTs.

4. CHOTs fabrication methods

Several CHOTs fabrication methods have been tried. They can be clustered into two groups: CHOTs fabricated directly on the testing component and CHOTs fabricated on a carrier substrate and then applied onto the testing component (transferable CHOTs).

Methods in the first category include: photolithography (figure 4(a)), spray painting through masks (figure 4(b)), metal deposition through masks (figure 4(b)), laser etching (figure 4(c)) and laser deposition [9] (figure 4(d)). Methods in the second category include layering a glass substrate with a dissolvable sacrificial layer and then spin coating the carrier layer, depositing the CHOT pattern through a mask and then releasing the carrier substrate (figure 4(e)). The transparent carrier is then attached on to the selected place for the testing of the component.

5. Results

Figures 5-9 present a selection of pitch-catch configurations using a variety of testing component materials (glass, aluminium, silicon nitride), geometrical shapes, ultrasonic directivity (plane and focused waves) and CHOTs fabricated with various methods. Figures 5(b), (c) and (d) show ultrasonic signal from a glass sample with CHOTs for plane SAWs designed for different ultrasonic frequencies (5, 10 and 20MHz). Figure 6(b) shows ultrasonic signal from a pair of CHOTs for 16MHz plane SAWs on Silicon Nitride (Si_3N_4). The signal has been recorded with broad electronic filtering (1MHz – 30MHz band pass range) and it shows the control on the generated frequency of the g-CHOT and the frequency filtering action of the d-CHOT. Figure 7 shows CHOTs made on aluminium components resembling turbine blades, fabricated using metal deposition through a laser etched mask (figure 7(d)). Figure 8 shows a g-CHOT which was directly laser etched onto the aluminium component. Figure 9(a) shows a g-CHOT fabricated with a combination of metal and ink deposition followed by selective laser removal of the ink. Figure 9(b) shows a g-CHOT fabricated on a transparent carrier. Figure 9(c) shows a pair of CHOTs on a glass substrate fabricated using laser deposition and figure 9(d) shows the ultrasonic signal generated and detected from these CHOTs.

6. Conclusions

CHOTs are a optically excited ultrasonic transducers which represent a cross between piezoelectric transducers and laser ultrasonics. They provide a simple method for generation and detection of ultrasound, wirelessly, remotely and with minimal impact on the inspected component. The CHOTs pattern controls the frequency, wavemode and directivity of the ultrasound and it requires a simple optical system to be excited. The CHOTs can be fabricated with a variety of methods that best suit the application they are intended for (permanent placement or in situ application). A portable prototype CHOTs pulser has been developed that is capable to excite CHOTs through an endoscope. This project is being developed for *in situ* ultrasonic inspection of aero-engines and will bring CHOTs closer to end-users applications. Our next step is to bring the portable CHOTs pulser to industrial facilities and demonstrate its capabilities.

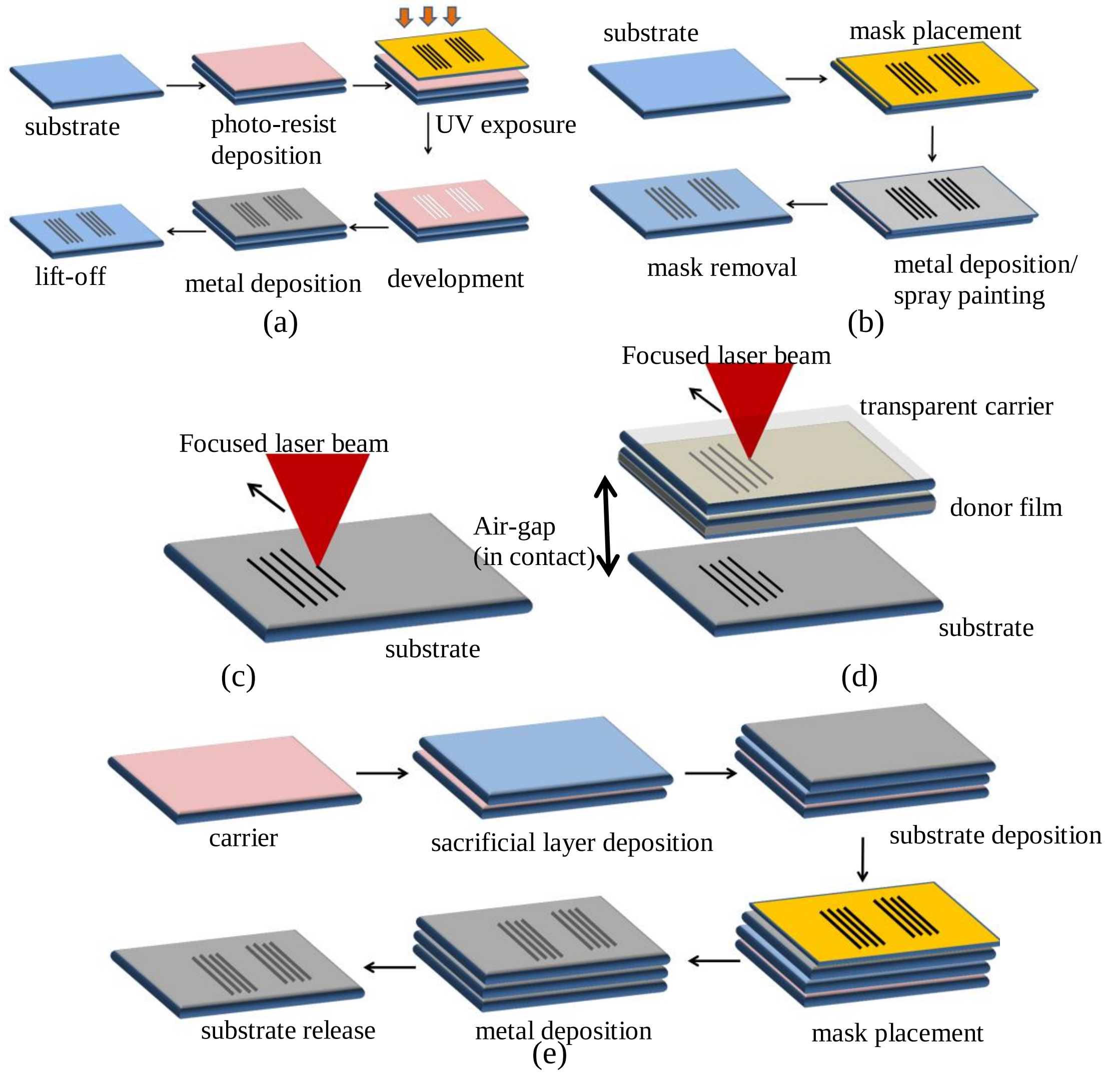


Figure 4. CHOT fabrication methods. a) Photolithography, b) Metal deposition or spray painting through masks. c) Direct laser etching. d) Laser deposition. (e) CHOTs on a carrier substrate.

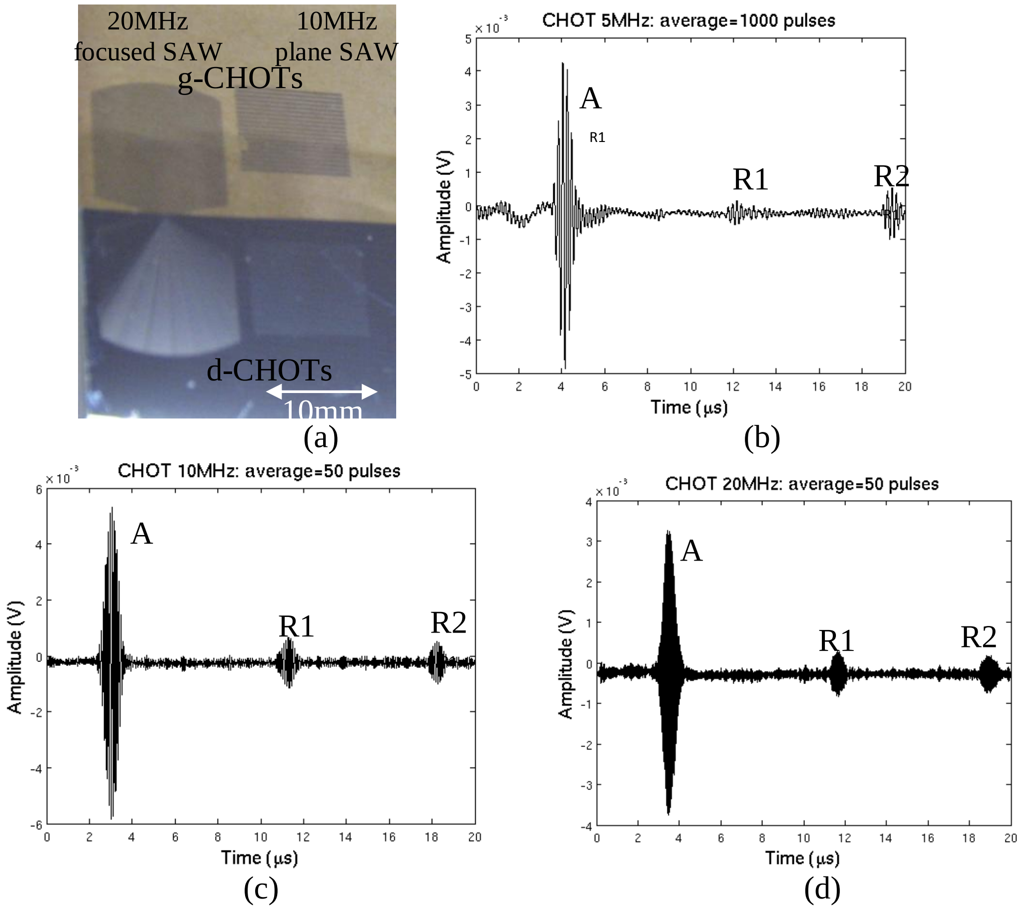


Figure 5. (a) Two pairs of CHOTs made using photolithography on BK7 glass. The CHOTs are made of aluminium. (b), (c), (d) show waveforms recorded from 5, 10 and 20MHz plane SAW CHOTs on glass, fabricated similarly to those shown in (a). The CHOTs were on the same glass sample. The waveforms show the pitch-catch signal (A) and two reflections (R1 and R2) from the sample's opposite edges.

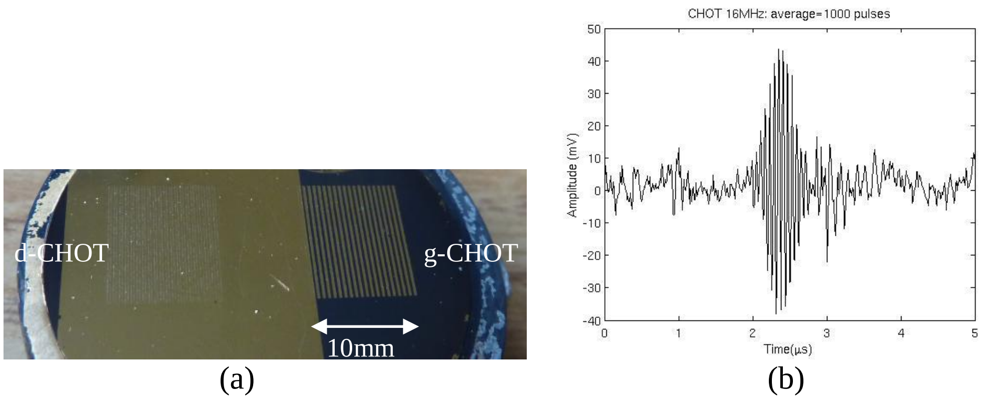


Figure 6. (a) Photo of a Si_3N_4 sample with a pair of CHOTs made using photolithography for 16MHz plane SAWs. The CHOTs are made of gold. (b) Waveform recorded using the CHOTs shown in (a).

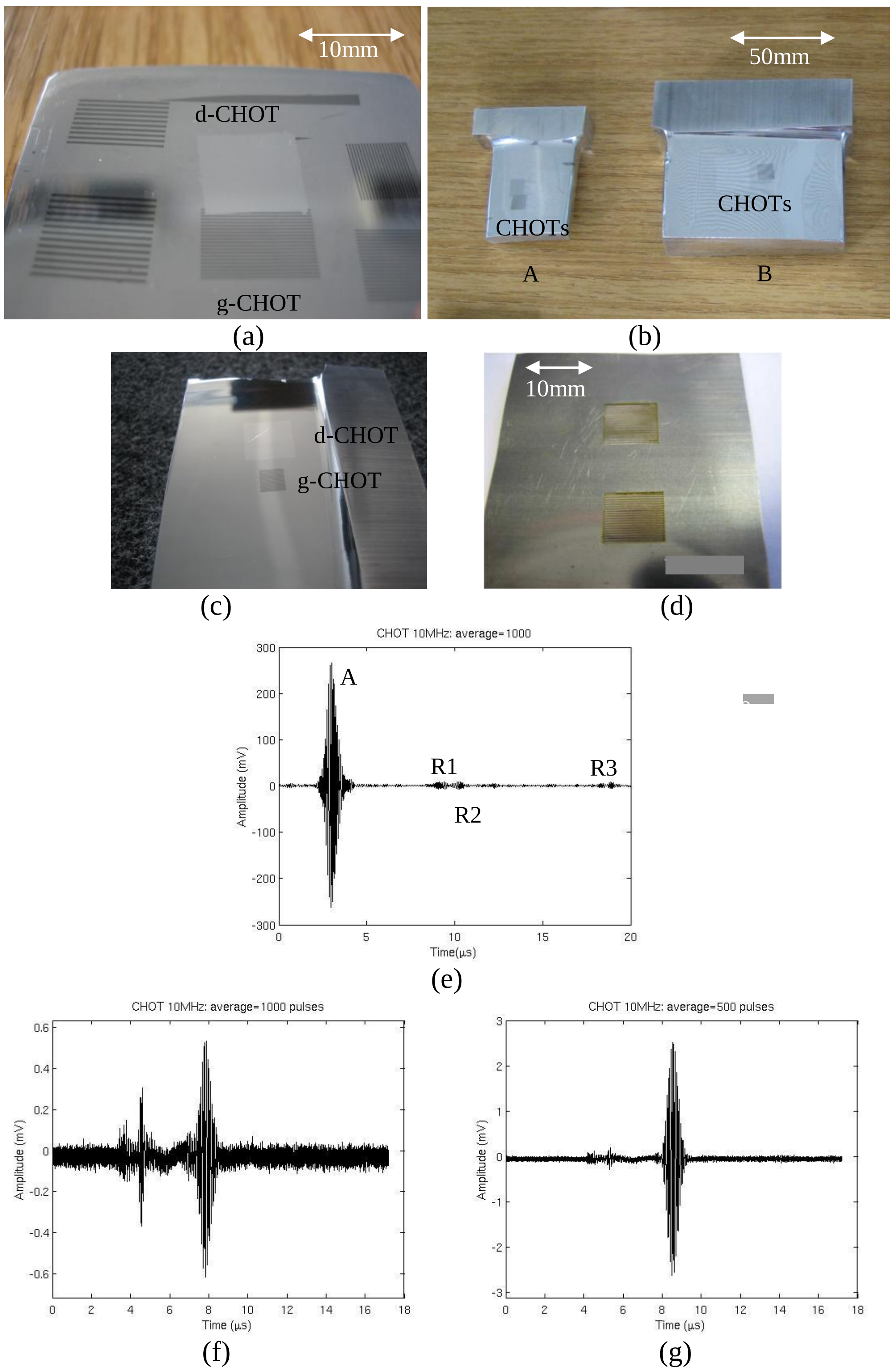
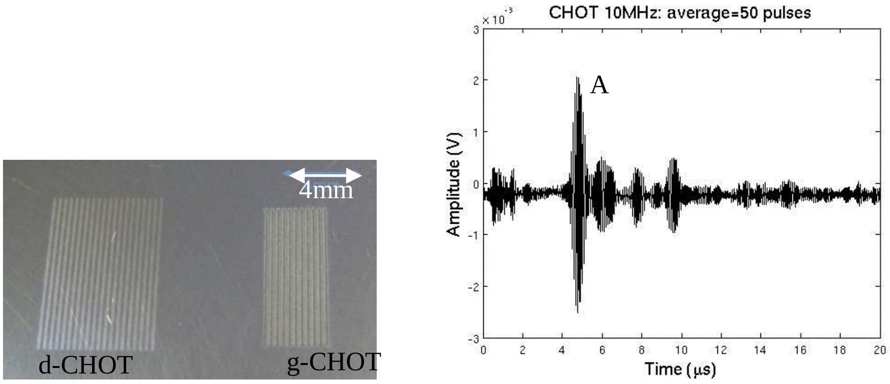
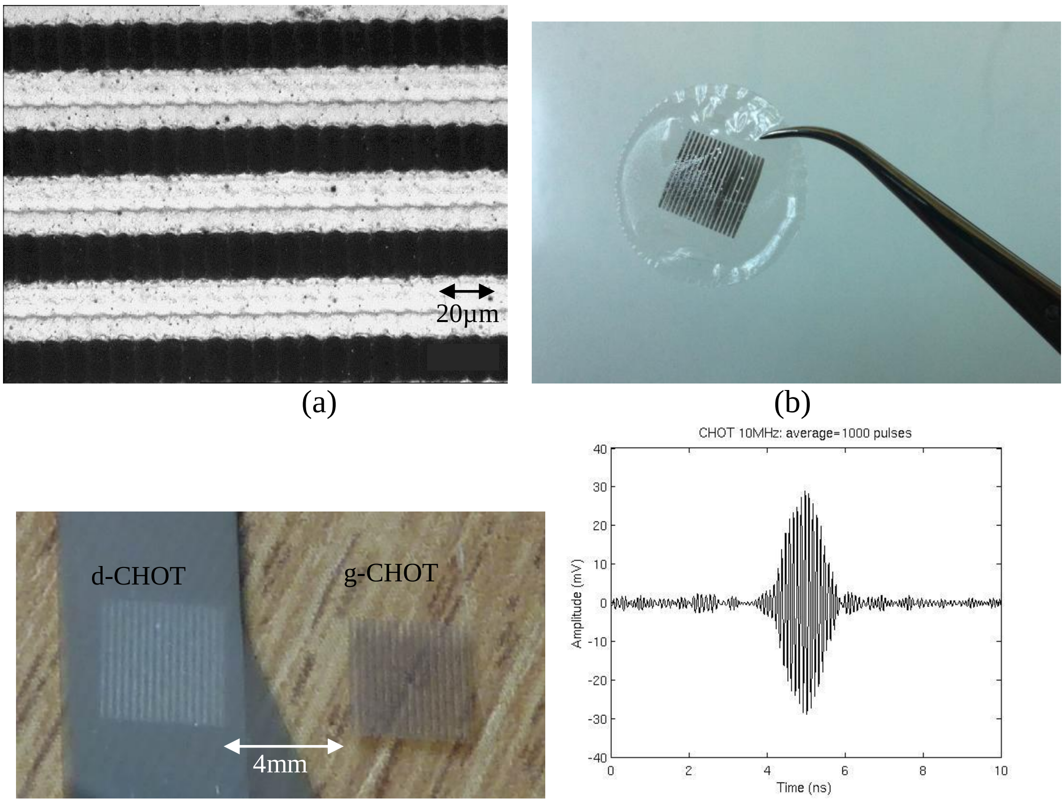


Figure 7. CHOTs made using metal deposition through mask on aluminium samples. The g-CHOTs are made of chrome and the d-CHOTs of aluminium. (a) 10MHZ CHOTs for generation and detection of SAWs. (b) 10MHz CHOTs on aluminium samples resembling turbine blades. (c) Close up of sample B shown in (b). (d) Laser etched mask used for making the CHOTs. (e) Pitch-catch signal recorded with CHOTs shown in (a). The first arrival (A) and some small reflections from the (rounded) edges of the sample (R2 and R3) as well as a surface defect (R1) are also shown. (f and g) Pitch-catch signals recorded with the CHOTs on samples A and B respectively, as shown in (b).



(a) (b)

Figure 8. (a) Photo of a pair of CHOTs on aluminium. The g-CHOT is made with direct laser etching on the sample. The d-CHOT is made with photolithography. (b) Waveform of pitch-catch signal recorded from the CHOTs shown in (a). The direct arrival (A) and several reflections from the sample (some of them from the etched g-CHOT lines) can be seen.



(c) (d)

Figure 9. a) g-CHOT fabricated on glass for generation of 82MHz plane SAWs. First a thin (200nm) layer of aluminium was deposited, then ink was spin coated on top and finally the ink layer was removed with a laser to produce the ink-aluminium CHOT pattern. b) Transferable CHOT on a SU8 substrate. b) Pair of CHOTs for generation and detection of 10MHz plane SAWs. The CHOTs were fabricated with laser induced forward transfer. c) Waveform of pitch-catch signal recorded with the CHOTs shown in c).

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References and footnotes

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