Novel Optical Transducers for Non-Linear Ultrasonic Applications

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Abstract. An innovative ultrasonic transducer system (CHOT) has been developed for applications in non-destructive testing. It is an ultrasonic transducer system that is optically rather than electrically activated using novel optical structures for detection and an optical pulser for generation. The method presents all the advantages of laser based ultrasound i.e. non-contact generation and detection, couplant free and easily adapted to surfaces with complex geometry. In addition, CHOTs (CHeap Optical Transducer) present some revolutionary advantages over both traditional ultrasonic transducers and conventional laser ultrasound. CHOTs have very low manufacturing costs and are very small in size with very low mass and profile. They can be disposable or permanently attached to the structure where they provide highly stable and reliable measurements. CHOTs are extremely simple to use, with extremely simple optics and have potential of high efficiency for ultrasonic generation and detection. Since laser generation and detection is used, the system can be completely remote (operation distance of hundreds of meters) which allows operation in hostile environments. Particularly for the purposes of non-linear ultrasonic experiments, CHOTs allow generation of narrowband ultrasonic signals of a chosen frequency and preferential filtering of harmonics. We present results where CHOTs have been used to generate and detect narrowband surface acoustic waves, however other types of wave modes can also be generated. Results are presented from three different chosen frequencies. We also demonstrate CHOTs' ability to detect defects and their capabilities in non-linear ultrasonic applications.

1. Introduction

Using ultrasound for the testing of materials is a powerful, well established and relatively simple technique: ultrasound propagates into the inner structure of the materials giving information about their properties, thickness and possible defects, to name but a few of the current applications. In the field of Non Destructive Testing (NDT) in particular, ultrasound has become an established technique and for certain applications narrowband excitation and/or detection is required.

Contact devices such as piezoelecrtic transducers are usually used to generate and detect ultrasound. However, there are certain disadvantages associated with conventional transducers. First of all, they generally require a coupling, which may be wet or dry but it introduces many problems to the inspecting system. These can be grouped in problems associated with scanning large surfaces (e.g.: drying of couplants or sensitivity variations from point to point), or a limited temperature range, which is particularly important for industrial applications. Other problems are related to the mass of the transducer itself, which might influence the measurements or the inspected structure and sometimes there are size considerations. Particularly in the case of hostile environments, a remote operation is preferable.

For the above reasons, we have concentrated our efforts in making an innovative ultrasonic transducer system which is optically activated both for generation and detection and that would address all the above mentioned shortcomings of the currently available transducers. CHOTs (Cheap Optical Transducer) are patterns that can be painted, drawn or attached on to the surface of the sample and consist of two parts: the g-CHOT (for generation) and the d-CHOT (for detection). They can be used as a coupled system or separately to either generate or detect ultrasound that is respectively detected or generated by other means.

CHOTs use lasers as actuators bringing the advantages of laser ultrasound in the narrowband frequency range. For the results presented in this paper, a Q-switched Nd:YAG pulsed laser emitting at 1064nm wavelength was used for ultrasonic generation and a cw HeNe laser emitting at 633nm wavelength was used for detection. The choice of laser for ultrasonic generation was based on the fact that Nd:YAG lasers are well adapted in the industry while the HeNe laser used for detection is a common found medium power laser that can also be fibre coupled. We have used CHOTs for generation and detection of surface acoustic waves, however they can also be used for other modes of waves by changing their pattern. We used BK7 glass samples for inspection to demonstrate the principle.

2. g-CHOT

Ultrasound is generated when the light emitted by a pulsed laser is absorbed from the material. In the low laser power thermoelastic regime there is no damage of the material and the process is nondestructive. The incident laser beam locally heats the sample surface and causes it to expand rapidly.

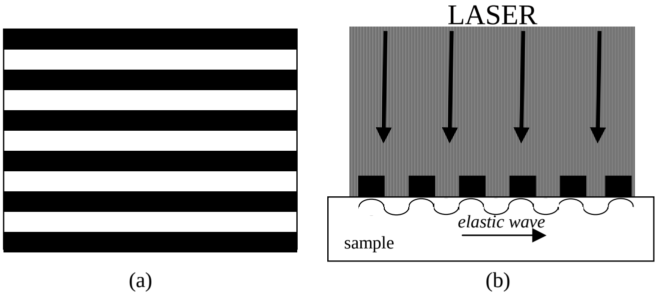


Fig.1 g-CHOT pattern for generation of surface waves (a). The substrate (white lines) is transparent/absorbing to laser radiation; the deposited layer (black lines) is respectively absorbing/reflective. (b) cross section of the sample. In this case, the illuminated area (laser spot size) is larger than the g-CHOT.

The idea behind the making of the g-CHOT is to create an ultrasonic source with an appropriately high contrast between absorbing and non-absorbing regions of the irradiated sample [1]. An example of such a structure is shown in Fig.1. This is the pattern that was used to generate plane surface waves of a chosen frequency in our experiments. The black lines represent areas where laser radiation is highly absorbed and the white lines represent areas where laser radiation is either transmitted or reflected. For example, the samples that we used for our experiments were made by BK7 glass. This material was chosen because it is highly transparent to the 1064nm radiation emitted by our Nd:YAG laser. We then created a pattern of aluminium stripes of the appropriate thickness corresponding to the ultrasonic frequency that we wanted to generate. Aluminium absorbs 1064nm radiation more strongly than the transparent substrate and thus creates the necessary contrast for the CHOT.

Laser ultrasound is usually associated with broadband generation. The bandwidth of the generated signal is related to the bandwidth of the laser pulse. For our experiments, the laser pulse and its frequency content can be seen in Fig.2 (a) and (b). It can be seen that the pulse duration of the laser is ~18ns and its spectrum extends up to ~30MHz. However, for our applications we wanted to generate narrowband ultrasound. The bandwidth is selected by tailoring the thickness of the lines of the illumination pattern [2].

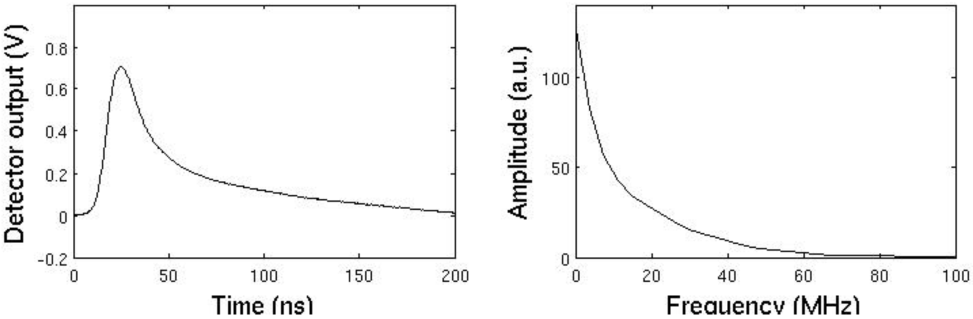


Fig.2 Nd:YAG: (a) Temporal profile. FWHM=20ns, rise time=9ns, (b) Frequency spectrum of the pulse.

2.1 Theory

Let us assume a single focused line (of infinitely small width) on the sample surface, of a laser beam with an infinitely short time duration (i.e. a delta pulse). It can be shown that, as long as the laser energy is absorbed in a layer much thinner than the ultrasonic wavelength (as is our case), the generated wave depends on the spatial and temporal characteristics of the laser pulse. Let us first assume a Dirac comb i.e. an infinite number of delta functions with spacing of width Δt_g, denoting the characteristic time that it takes for the acoustic wave to propagate between two adjacent lines and which is related to the spacing between the individual lines of width w_g and the surface wave velocity c. It follows that the frequency content of the generated ultrasound would be another Dirac comb where the adjacent lines would have a spacing of $1/\Delta t_g$. Since the number of lines in the g-CHOT pattern is not infinite but N_g, we can represent this by multiplying the Dirac comb with a top hat function that will include N_g lines. Again, the individual lines of the g-CHOT pattern are not infinitely small but have a width of w_g and we can further assume that each one has a top hat spatial profile. In order to include this we have to convolve the initial Dirac comb with the lines' profile. In this analysis we have assumed that the laser pulse is infinitely short in time. If, in addition we consider the temporal profile of the laser, then we would have to convolve the laser pulse with the spatial profile of the previous analysis. The above-described analysis is represented in Fig.3 (similar theoretical analysis can be found in chapter 2 of [3]). The of the generated ultrasound depends on the number N_g of g-CHOT's lines that are illuminated by the laser pulse.

The above-described theory behind the g-CHOT has been used in the past [4-10] and it is the principle behind the operation of the Optical Scanning Acoustic Microscope (OSAM) developed from our group [11-12]. However, all the previous techniques required temporal and spatial tailoring of the laser beam. As a result most of these systems suffer from one or more of the following: they are expensive, require careful alignment and knowledge of optics, may be bulky, need a highly experienced operator and are difficult to adapt in an industrial environment.

With g-CHOTs, instead of modifying the laser beam, the sample surface is slightly modified to provide the necessary absorption contrast. The laser is a typical Q-switched

Nd:YAG, all the optics involved are very crude and the beam can be delivered via a fibre. In addition, the user has a choice of generating frequencies, limited only by the bandwidth of the laser pulse. For example, the laser used in this study had a bandwidth between 0-30MHz (as seen in Fig.2). By changing the spacing of the absorbing lines on the g-CHOTs pattern we were able to choose 5, 10, 20MHz narrowband ultrasonic generation and we simply need to resolve the whole pattern rather that its details.

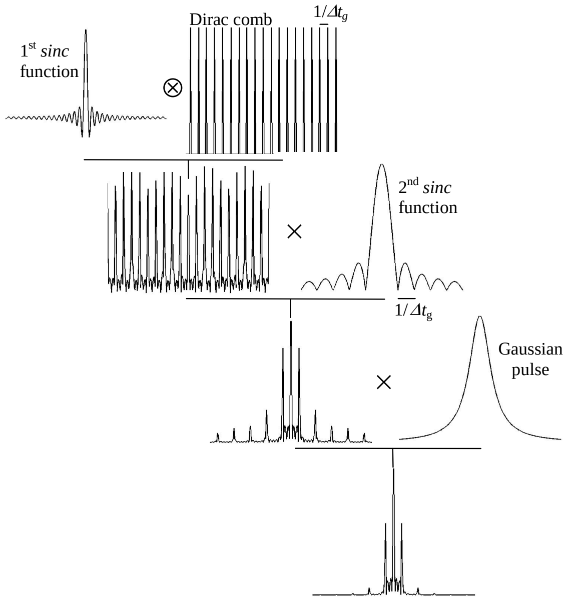


Fig.3 Graphic representation of the frequency filtering action of the g-CHOT.

3. d-CHOT

It is in the interests of the user to limit the bandwidth of the detection system (provided that no useful signal is lost in the process) [6]. In addition, for several applications and especially in nonlinear ultrasonic experiments, there is a need for a detection system, sensitive enough to measure the low amplitude harmonics and which can provide reliable measurements without introducing extra non-linearities to the inspection system. During the development of a laser based system it is often preferable for the detection to be based on lasers as well, since this method is also non-contact and couplant free. For these reasons we concentrated our efforts on developing a detection system that would make best use of the g-CHOT.

The d-CHOT consists of a pattern on the surface of the sample, which reflects light. It is in effect a reflective grating. The grating consists of appropriately designed steps, which introduce the desired path difference to the light (Fig.4). Again, the operation is remote and the actuator is a laser, which simply illuminates the area of the grating. The beam reflected by the d-CHOT is separated into various diffraction orders and the main reflection (zero order). The latter is separated from the rest by means of an iris and directed onto the photodetector. The height of the steps (*h*) of the d-CHOT for normal incidence corresponds to 1/8th of the optical wavelength. In our case, we were using a medium power cw HeNe laser, emitting at 633nm wavelength, i.e. the height of the steps should be ~79nm. For this configuration, 50% of the incident laser energy is directed to the zero order. When the generated ultrasound travels below the area of the d-CHOT, this height changes, thus modulating the amount of energy directed to the zero order. It is this modulation that is detected by the photodiode. In effect, the d-CHOT is a miniature two beam interferometer. Its advantages however are that, because the effective path difference between the “signal beam” and the “reference beam” is of the order of ¼ of the wavelength of the detection laser, it is very stable and can be easily adapted into noisy industrial environments. In addition, because it makes use of the direct specular reflection (zero order) of the grating, it can be used with samples that are not rigorously polished as long as there is enough light to provide enough detectable signal.

At the same time, the d-CHOT is filtering the detected ultrasonic signal. The spacing of its lines corresponds to the distance travelled by the ultrasonic wave of the desired frequency. For example, in our case, we were generating surface waves on BK7 glass and we wanted to detect ultrasound at f_d=5, 10 and 20MHz. The spacing of the grating was $s_d=c/f_d$. In this way the d-CHOT filters the ultrasound with the appropriate frequency providing narrowband detection.

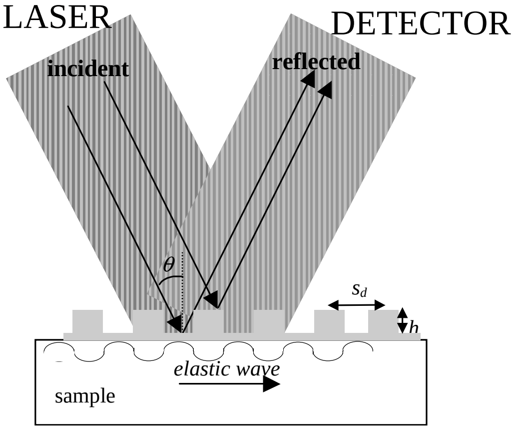


Fig.4 d-CHOT pattern (cross section): reflective material (in light grey) with appropriate height (h) and spacing (s_d) to detect ultrasonic waves.

Following a similar analysis with the g-CHOT, if one assumes that a broadband source (such as a laser focused onto a single line) generates ultrasound, then the frequency spectrum of the signal detected by the d-CHOT would be the convolution between a Dirac comb and a *sinc* function representing the top hat function that includes N_d number of lines and another multiplication with a *sinc* function corresponding to the top hat spatial profile of each individual line of the d-CHOT grating.

As with the g-CHOT, the bandwidth of the peaks depends on the number of illuminated d-CHOT lines and the larger the number of illuminated lines, the narrower the bandwidth. In this way, the d-CHOT has a great potential for highly efficient ultrasonic detection.

4. CHOT System

Combining the analysis for the g-CHOT and the d-CHOT, it can be seen that when the two elements of the CHOT are combined in one system for generation and detection, then the frequency bandwidth of the resulting signal will be the product of the two frequency contents.

5. Experimental Results with CHOT System

Experiments have been performed to demonstrate the operation of the g-CHOT and the d-CHOT as narrowband transducers for generation and detection as a coupled system. A BK7 glass sample of size 50mm x 50mm and thickness 8mm, was used. The surface wave velocity of the sample was measured using the OSAM system [13] and was found to be 3370m/s. The CHOTs were manufactured by photo-lithography. The absorbing stripes of the g-CHOT were made by evaporating an aluminium coating of ~318nm thickness. The laser used as an actuator for the g-CHOT was a Q-switched Nd:YAG laser emitting at 1064nm wavelength of pulse duration 20ns, 300mW of power and 1kHz repetition rate.

The d-CHOT was made by evaporating a thin (~160nm) coating of aluminium initially, to make the surface reflective and then the stripes were made by a second layer of aluminium creating steps of ~70nm height. For optimum operation and at normal incidence of the d-CHOT, the height of its steps should have been 1/8 of the detection laser wavelength. Since we were using a HeNe laser emitting at 633nm, the optimum step height should have been 79nm. Thus, we were not operating at optimum conditions. In addition, the angle of incidence was estimated to be ~35^o due to the experimental setup, meaning that the path difference was ~115nm (path difference=2(step height)cosθ) instead of 158nm. The HeNe laser was operating at cw mode and its power output was 10mW.

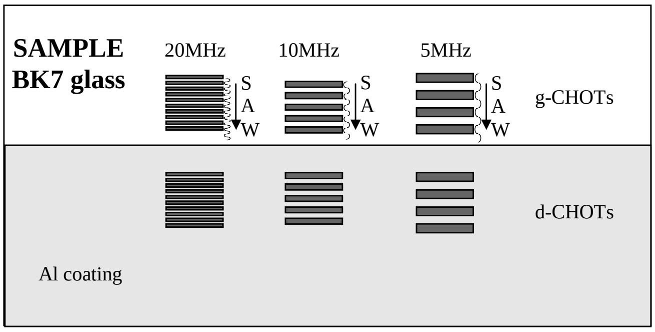


Fig.5 Schematic representation of coupled CHOTs.

Three different pairs of CHOTs were made on the same sample. One with line (and spacing) thickness corresponding to the generation and detection of 5MHz SAWs (thickness=336μm), one for 10MHz SAWs (thickness=168μm) and one for 20MHz SAWs (thickness=84μm). The number of lines in each CHOT for the 5MHz, 10MHz and 20MHz system, was 10, 20 and 40 respectively. Each CHOT was 0.8cm x 0.6cm in size and the g-CHOT was separated from the d-CHOT by ~1.2cm. A representation of the sample's surface can be seen in Fig.5.

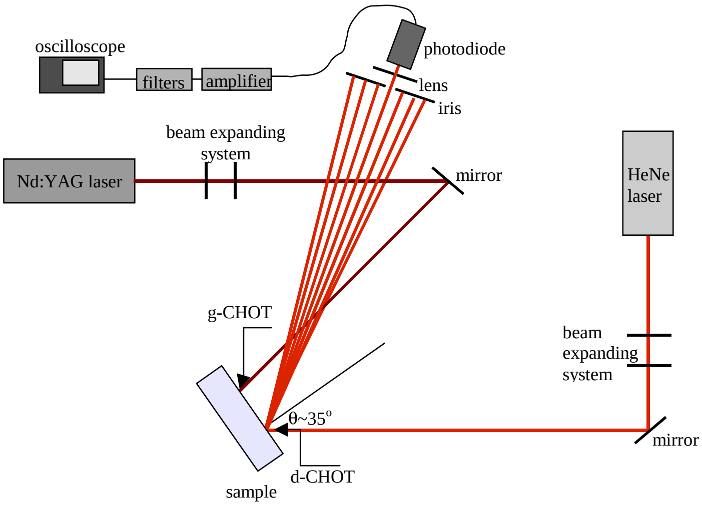
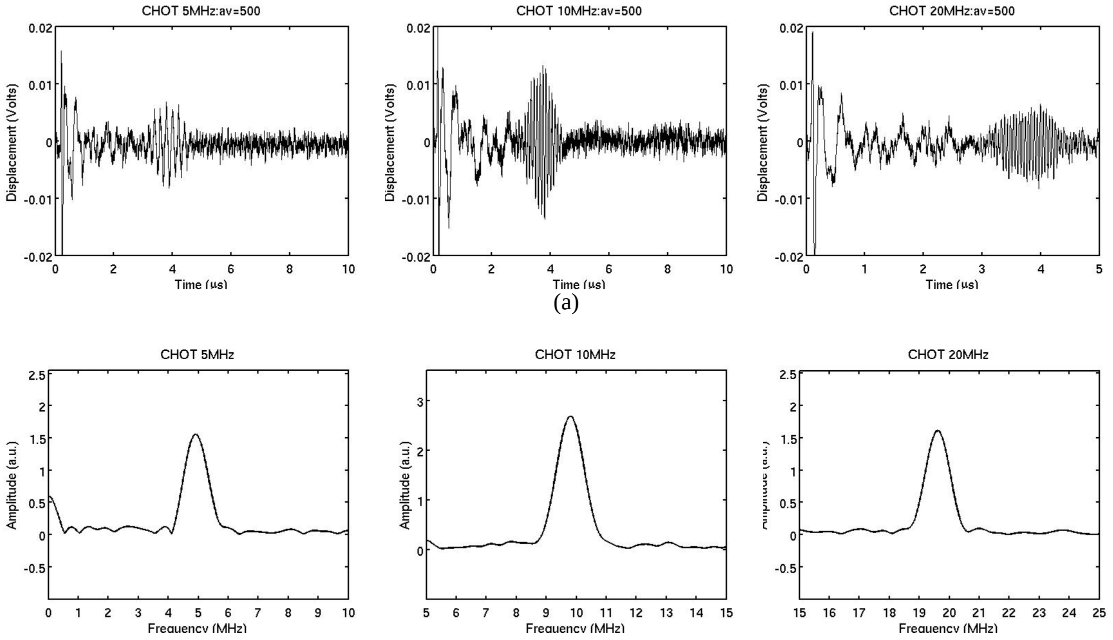


Fig.6 Experimental setup for coupled CHOT system.

The experimental setup is depicted in Fig.6. The spot size of the generating beam on the surface of the sample was controlled by a lens system and was 0.5cm in diameter (i.e. 40% of the area of the g-CHOT) while the incident energy was kept constant at 300mW at1kHz repetition rate (corresponding to energy density of 1.53mJ/cm^2). The spot size of the detecting beam was also ~0.5cm diameter. The various diffraction orders and the directly reflected beam were separated by means of an iris and the remaining beam was then focused onto a photodiode. The signal was initially filtered with a 3MHz high pass filter and a 21.4MHz low pass filter. It was then amplified and finally captured on the oscilloscope. The captured waveforms can be seen in Fig.7(a). The signal was averaged over 500 pulses. The initial electronic noise marks the beginning of the generation laser pulse. Fig.7 (b) shows the frequency content of the corresponding signals.



(a)

(b)

Fig.7 Experimental results: (a) waveforms captured using CHOT system for 5, 10 and 20MHz; the electronic noise at the beginning of the graph marks the beginning of the generation laser pulse, (b) frequency content of the respective waveforms.

6. Conclusions and Future Work

In this paper we have presented a new concept of optical transducers, the CHOTs, and shown experimental results from their operation. They consist of a generation (g-CHOT) and a detection (d-CHOT) part and can be used either as a coupled system or individually. Lasers are used as actuators providing remote and couplant free operation. Amongst its many advantages over traditional contact transducers is their low profile (minimal weight and size <1cm^2) allowing minimal impact to the inspected sample and that it can be permanently attached to the sample to provide reliable and repeatable measurements. In addition, they have the potential of becoming very cheap. For the g-CHOT, the pulsed laser is used as the actuator providing a wide selection of frequencies limited only by its broadband frequency spectrum (dependant on the laser's pulse duration) and its energy. Thus, the user, by choosing the appropriate g-CHOT, can have a wide selection of narrowband exciters. In our experiments we used a Nd:YAG laser emitting at 1064nm. Such lasers have been fully adapted in the industry because they can be portable, they need little maintenance and they are becoming continuously less expensive. The laser we used had a rise time of10ns (corresponding to a useful frequency content extending up to ~30MHz) and delivered enough energy to excite 5, 10 and 20MHz ultrasonic signals as demonstrated. For the d-CHOT, a medium power laser is suitable. We used a cw HeNe laser emitting at 633nm and 10mW of power. This proved sufficient for detecting the ultrasound generated by the g-CHOT. The d-CHOT takes advantage of the direct reflection of the laser beam and for this reason it does not have high demands on the reflectance of the sample surface.

Amongst the applications that CHOTs is most suitable for is Nonlinear Elastic Wave Spectroscopy (NEWS). NEWS techniques have shown to be more sensitive in detecting microscale fractures and predicting early damage [14] than traditional linear acoustical methods. The concept of NEWS-based methods is that internal damage can be measured directly with the instantaneous detection of an increase in the nonlinearity parameters. This is the research objective of a large scale European project (AERONEWS) in which our group participates. In order for non-linear measurements to be reliable the ultrasonic generation and detection systems should be free from non-linearities to begin with and for the detection system in particular, it should have high sensitivity in order to receive the generally small signals associated with harmonics. For example, a g-CHOT can generate the fundamental chosen so that the harmonic lies outside the frequency content of the generating laser. The d-CHOT then is sensitive enough to detect and monitor the harmonic that is indicative of the presence or the development of a defect [15]. In another example, a g-CHOT pattern combining two different frequencies (one high and one low) can be used in experiments of frequency mixing [16]. In this case the d-CHOT detects the high frequency and the non-linear parameter is measured by the phase modulation observed in the high frequency. We are currently in the process of realising such experiments.

In the future, we plan to experiment with other manufacturing processes, making the preparation of the CHOTs faster and cheaper, but also to increase the efficiency of the CHOT system.

7. References

[1] Bonello B. and Ajinou A. (2001) Surface acoustic waves in the GHz range generated by periodically patterned metallic stripes illuminated by an ultrashort laser pulse. *J. Acoust. Soc. Am.* **110**(4), 1943-1949.

[2] Lin H.-N., Maris H.J. and Freund L.B., Lee K.Y., Luhn H. and Kern D.P. (1993) Study of vibrational modes of gold nanostructures by picosecond ultrasonics. J. Appl. Phys. 73(1), 37-45.

[3] Hutley M.C. (1982) Diffraction gratings, London: Academic Press.

[4] Auth D.C. (1970) New high-power source of coherent microwave phonons. Appl. Phys. Lett. 16(12), 521-523.

[5] McKie A.D.W., Wagner J.W., Spicer J.B. and Penney C.M. (1989) Laser generation of narrow-band and directed ultrasound. Ultrasonics 27, 323-330.

[6] Wagner J.W., Deaton J.B. Jr., McKie A.D.W. and Spicer J.B. (1990) Laser ultrasonics: generation and detection considerations for improved signal-to-noise ratio. Proceedings of SPIE 4915, 491-501.

[7] Jarzynski J. and Berthelot Y.H. (1989) The use of optical fibers to enhance the laser generation of ultrasonic waves. J. Acoust. Soc. Am. 85(1), 158-162.

[8] Huang J., Krishnaswamy S. and Achenbach J.D. (1992) Laser generation of narrow-band surface waves. J. Acoust. Soc. Am. 92(5), 2527-2531.

[9] Edwards C., Bushell A.C., Palmer S.B. and Nacano H. (1992) Laser interference grating for surface wave generation. Nondestr. Test. Eval. 10, 15-23.

[10] Liu Y.-H., Wu T.-T. and Lee C.-K. (2002) Application of narrow band laser ultrasonics to the nondestructive evaluation of thin bonding layers. J. Acoust. Soc. Am. 111(6), 2638-2643.

[11] Clark M., Sharples S.D. and Somekh M.G. (2000) Fast all-optical Rayleigh wave microscope: imaging on isotropic and anisotropic material. IEEE Trans. Ultras. Ferr. Frequ. Contr. 47(1), 65-74.

[12] Hong Y., Sharples S.D., Clark M. and Somekh M.G. (2003) Rapid measurement of surface acoustic wave velocity on single crystals using an all-optical adaptive scanning acoustic microscope. Appl. Phys. Lett. 83(16), 3260-3262.

[13] Sharples. S.D., Clark M., Somekh M.G. (2005) Fast noncontact imaging of material microstructure using local surface acoustic wave velocity mapping. Proc. 2005 IEEE Ultrason. Symp. 886-889.

[14] Bulk O., Morris W.L. and Richardson J.M. (1978) Acoustic harmonic generation at unbonded interfaces and fatigue cracks. Appl. Phys. Lett. 33(5), 371-373.

[15] Blackshire J.L., Sathish S. and Frouin J. (2003) Nonlinear laser ultrasonic measurements of localised fatigue damage. Review of Progress in Quantitative Nondestructive Testing, Ed. Thomson D.O. and Chimenti D.E. 22, 1479-1488.

[16] Vila M., Vander Meulen F., Dos Santos S., Haumesser L., Bou Matar O. (2004) Contact phase modulation method for acoustic nonlinear measurement in solid. Ultrasonics 42, 1061-1065.