ULTRASONIC DETECTION SYSTEM BASED ON TWO-WAVE MIXING IN PHOTOREFRACTIVE GAAS CRYSTAL

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The generation and the detection of ultrasound at distance by lasers present many advantages over conventional piezo-electric based methods. In particular, it can be used on surfaces of complex geometry and on products at elevated temperature on a production line [1,2]. Detection has been so far usually performed by using interferometers with passive elements, the most useful being the confocal Fabry-Perot interferometer used in a transmission or reflection mode. [1,3-5].

Passive interferometers for surface motion detection can be advantageously replaced by active or adaptive interferometers based on two-wave mixing in photorefractive crystals. In these systems, a signal beam, which acquires phase shift and speckle after reflection on a surface in motion, is mixed in a photorefractive crystal with a pump plane wave to produce a speckle adapted reference wave that propagates in the same direction as the transmitted signal wave and interferes with it. We have recently devised and demonstrated such a scheme, as sketched in fig 1, by using two-wave mixing in a photorefractive $BaTiO_3$ crystal [6]. Since in this case, charge separation is essentially caused by diffusion, the transmitted signal wave and the reference wave are approximately in phase, thus leading to quadratic detection. Linear detection was obtained by giving two polarizations to the input signal wave and adding a retardation plate at the output, so the reference and transmitted waves were in quadrature [6].

In order to use a photorefractive interferometer for ultrasound detection in most industrial conditions, the grating build-up and erasure time (τ) should meet stringent specifications. First, it should be sufficiently long to properly generate the reference beam, which means that the grating should not follow the motion of the interference pattern

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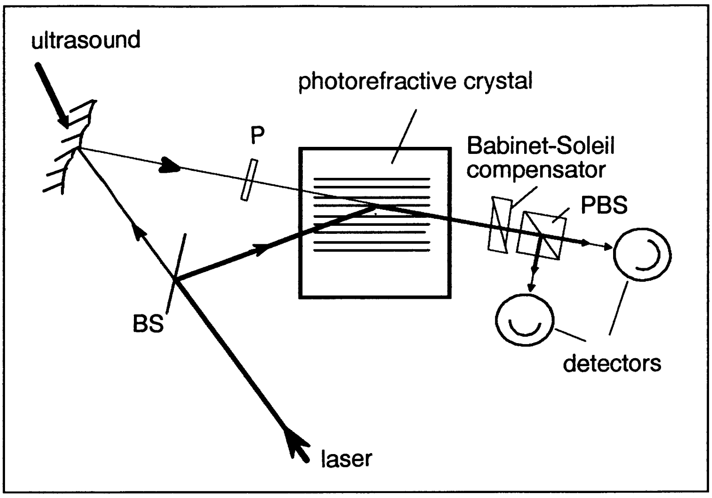

Figure 1: Basic experimental set-up for optical detection of ultrasound by two-wave mixing in a GaAs crystal. P is a polarizer and PBS a polarizing beam splitter, both being oriented at 45° to the plane of incidence, BS is a beam splitter.

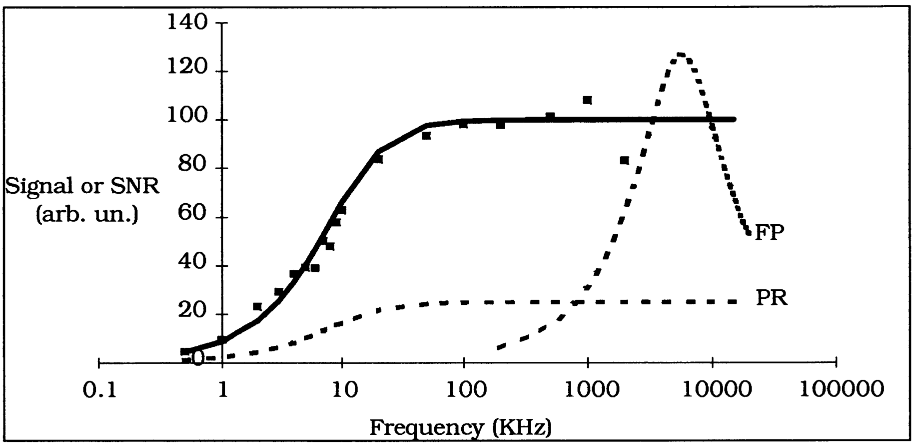

Figure 2: Amplitude of the modulated intensity (arb. units) versus the frequency (kHz) of the phase modulation; square: experimental, solid curve: calculated. Experimental conditions : total incident intensity = 40 W/ cm^2, pump to signal intensities ratio = 100, angle between beams = 60°. We also plot on the same figure in dashed line the signal-to-noise ratio (arb. un.) versus frequency of a confocal Fabry-Perot interferometer (FP) used in transmission 1 m long with 85 % reflectivity mirrors [5] and of the photorefractive system (PR) (assuming the same bandwidth and the same received power).

induced by the signal transient phase shift. It should be also sufficiently short, so the device is not sensitive to low frequency ambient vibrations and adapts itself to the rapid change of the speckle pattern when the inspected product is moving or the inspected location is changed. An additional reason for a short response time is to allow the use of a higher power pulsed laser. The higher laser power compensates for the return losses associated with the scattering and absorbing surface and the long propagation paths. In practice these requirements mean a value of τ around 10 μs, a value much below the present capability of $BaTiO_3$, but which is possible with semiconductor photorefractive materials.

We have built and tested the interferometric system based on undoped GaAs crystal in the diffusion regime. A complete description of this device could be found in ref. [7]. In brief, the laser used was a 500 mW-cw-diode-pumped Nd:YAG laser operating at 1.064 μm. We used a 5 mm x 5 mm x 5 mm undoped GaAs crystal grown by liquid encapsulated Czochralski method and cut along the 001, 110 and -110 directions. The absorption coefficient at 1.064 μm was measured to be 1.5 $\pm$ 0.1 cm^{-1}. The input and output surfaces were anti-reflection coated. Two-wave mixing at 1.064 μm in undoped GaAs in the diffusion regime has been first reported by Klein [8]. We have found the same two-wave mixing maximum gain coefficient of $\Gamma_{max} = 0.4$ cm^{-1} for an angle of 60° between the pump and the signal beam outside the crystal. The interferometer output modulated intensity (ΔI) versus the modulation frequency is plotted in figure 2. We have checked that the plateau observed in figure 2 spreads up to at least 20 MHz. The theoretical variation of ΔI with frequency has previously been derived using a simple model of the photorefractive effect and has been shown to be proportional to the following function [9] :

$$\Delta I \propto \frac{2\pi\nu\tau}{\sqrt{1+(2\pi\nu\tau)^2}} \qquad (1)$$

where τ is the writing time constant of the grating. By fitting the expression to the data of figure 2, we find τ = 14 μs. One may note that this time constant depends on the angle between the beams and on the incident light intensity [8]. In our measurement, the total incident intensity was about 40 W / cm^2, the pump to the signal beam ratio was 100 and the angle was 60°. The detection limit, defined as the surface displacement which produce a unitary signal-to-noise ratio, depends upon the power of the signal beam and of the electronic bandwidth, after reduction to unitary signal power and bandwidth, we measured in the photon noise regime a limit of 1.56 x 10^{-5} Å $(W/Hz)^{1/2}$. This value is about 5 times the value obtained with a confocal Fabry-Perot interferometer in the range of maximum sensitivity where it is generally used [3]. Therefore, this system is from this point of view less attractive, when working in the range usually used for non-destructive inspection (~ 1-20 MHz), although its detection bandwidth is broader, especially at low frequencies (see Fig. 2). It can then be estimated that this system has better sensitivity than a typical confocal Fabry-Perot (1 meter long, 85 % reflectivity mirrors, used in transmission) up to 0.75 MHz. The detection limit of our device could be reduced to 5×10^{-6} Å $(W/Hz)^{1/2}$ by using the optimum crystal length and the cross-polarized two-wave mixing geometry [7].

Concerning the étendue or throughput, a first approach consists in finding the limit incident angle for plane wave illumination that reduces the output of the interferometer by a factor of two. From the measured values of the gain versus the angle between the beams, we find a limit angle of about 45°. Assuming further an effective crystal aperture of 3 mm in diameter, the étendue calculated following this approach is 4.2 mm^2 sr. This value is much greater than the one obtained with a confocal Fabry-Perot (typically ~0.4 mm^2.sr for a Fabry-Perot 1m long with 85% reflectivity mirrors) [3]. This large value has not been experimentally verified with a speckle beam of comparable étendue, but we have nevertheless verified that the system work without any reduction of sensitivity with a speckle signal beam produced by a multimode optical fiber having the typical étendue mentioned previously (~ 0.4 mm^2 sr).

In addition to the experiments performed with a cw Nd:YAG laser, we have implemented this detection scheme into a complete laser ultrasonic system. In this system, in order to optimize sensitivity, two 5 mm^2 GaAs crystals are used in series with the crossed-polarized configuration. The crystals are also anti-reflection coated.

This laser ultrasonic system also includes a TEA CO_2 laser with pulse duration of about 120 ns for generation of ultrasound. The probe beam, which is produced by a pulsed YAG laser with pulse duration of 70 μs, is transmitted by an optical fiber and focused to a diameter of 4 mm^2 onto the surface of the sample. The CO_2 laser pulse is fired near the maximum of the YAG pulse giving an interval of about 20 μs with no significant variation of probe beam intensity. The light scattered by the surface of the sample is collected by lenses and brought to the photorefractive detection unit by a second optical fiber. The light power scattered by the surface is typically of the order of few milliwatts. After transmission by the fiber, the collected light is finally focused onto the two crystals and mixed with a pump beam directly picked up at the output of the YAG laser. The angle between the pump and signal beams is about 70°.

Detection is performed by two detectors mounted in a differential scheme. The resulting electrical signal is then amplified by a broadband amplifier and pass through a lowpass filter before being digitized and saved for later analysis. The bandwidth of the system is limited by the crystal, the AC coupling capacitors following the detectors and a lowpass filter, resulting into a bandwidth of 10 KHz to 17.5 MHz.

We present here preliminary results obtained with this system on two cross-ply graphite-epoxy samples of thicknesses, 5 mm and 13 mm. For the results reported here, generation and detection were performed on opposite sides of the samples, the detection side being painted to increase the level of scattered light. The data was averaged over 32 consecutive shots. A background level resulting from improperly balanced detectors was subtracted from the differential signal. The experimental data were also normalized to take into account the envelope of the detection YAG laser.

Figure 3 shows the results obtained with the 5 mm thick sample. Three longitudinal mode echoes are clearly visible and a fourth one can

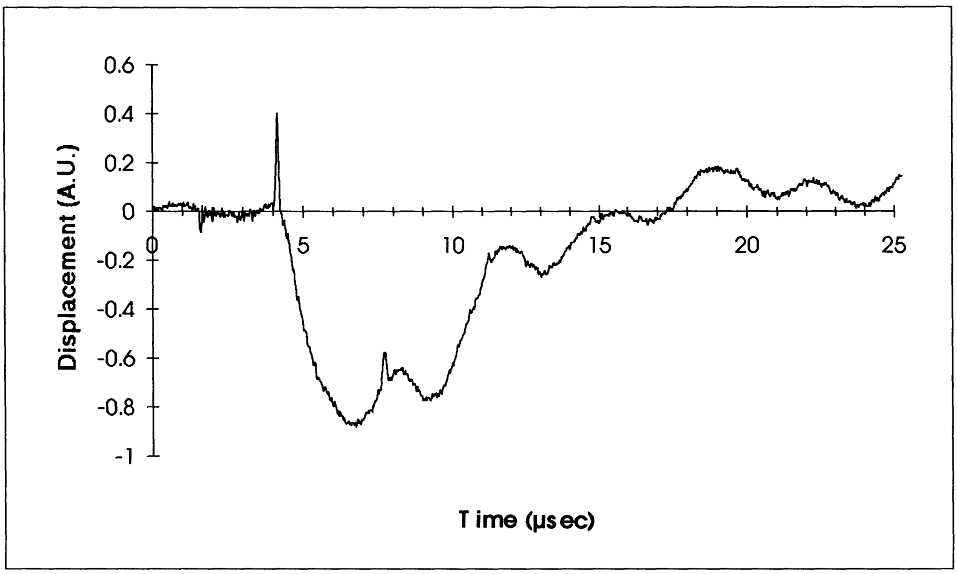

Figure 3: Displacement (arb. units) of the surface of the 5 mm thick composite sample obtained with the photorefractive system.

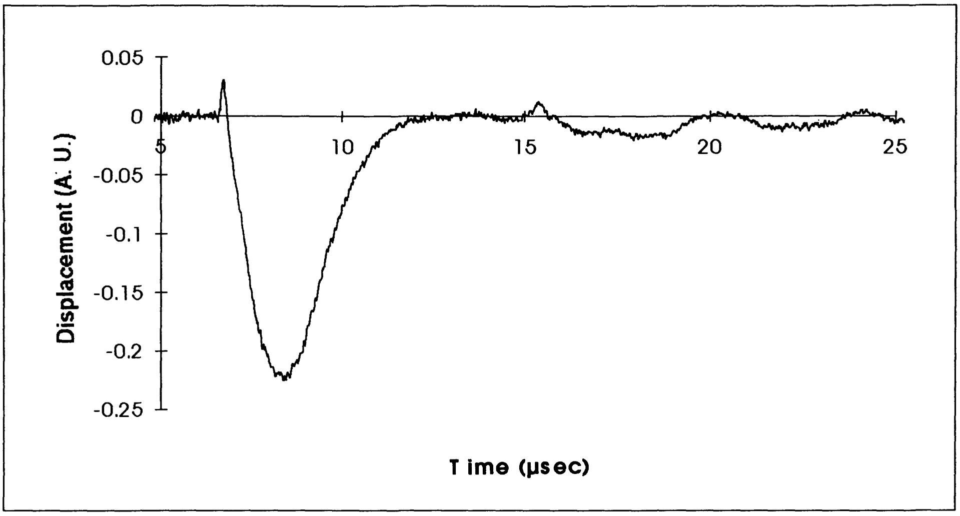

Figure 4: Displacement (arb. units) of the surface of the 13 mm thick composite sample obtained with the photorefractive system.

be localized easily. These echoes have a unipolar shape, which demonstrates the broad detection bandwidth of the system. In addition, we can see very clearly the low frequency variation associated with shear and mode conversion. In a Fabry-Perot detection system the observed echoes are instead bipolar and the low frequency variation is typically filtered out. Signals of this kind are also observable with heterodyne probes [10]. However in this case detection is performed over a point and is speckle sensitive. One notes also in figure 3 that the signal returns near the zero baseline with a time constant of the order of 10 μs. This value corresponds roughly to the response time of the crystal (it is however slightly modified by the low frequency cut-off of the electronics following the detectors).

Figure 4 shows the results obtained on the 13 mm thick sample. Only two echoes are visible, the second one being smaller and much broader than the first one because of material attenuation.

In conclusion, we have developed an interferometric detection system that has a broad detection bandwidth, extending in particular down to 10 kHz, and that is furthermore speckle insensitive. Preliminary data have been shown, which demonstrate its use on composite materials.

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