OPTICAL DETECTION OF SUB-ANGSTRÖM TRANSIENT MECHANICAL DISPLACEMENTS

D. ROYER and E. DIEULESAINT

Laboratoire d'Acoustoélectricité de l'Université P. et M. Curie,
ESPCI - 10 rue Vauquelin - 75231 PARIS Cedex 05 - FRANCE

ABSTRACT

Our compact heterodyne optical interferometer used for measuring harmonic displacements as low as 10^{-4} Å in a one Hertz bandwidth has been modified by the addition of a wide bandwidth electronic circuitry. This makes it suitable for measuring transient mechanical displacements. The results presented concern the mechanical impulse response of bulk and surface wave piezoelectric transducers and the detection of mechanical displacements generated in a metallic plate by a YAG laser pulse. The sensitivity achieved is 0.4Å in a bandwidth of 50 MHz.

1 - INTRODUCTION

The operation of the acoustic wave components and devices depends mainly on the characteristics of the beam transmitted by the transducer and on the conditions of propagation. The nature, shape, dimensions, homogeneity of the transducer (usually piezoelectric), the matching to the signal generator and the backing play a major part in the generation of the waves. As the waves propagate, they are diffracted, partially absorbed ; inhomogeneities causing local reflexions and changes of velocity. It is thus useful to examine the acoustic field at its origin and at some steps of its propagation.

The methods are different according to the type of waves and the medium of propagation. For instance, low frequency bulk wave transducers used in medical imaging or in non destructive testing can be checked in water with the aid of a small piezoelectric receiver (1) or a reflective ball (2). Surface acoustic waves used for signal processing are investigated by optical techniques (beam deflexion(3, 10, 11), interferometry (4)). The interferometric probes are also suitable for bulk waves.

These optical techniques have the advantages of probing a small area, requiring no mechanical contact, however they are less sensitive than piezoelectric probes. Consequently, they are usually applied to measurements only at a selected frequency. The preference given to harmonic regimes derives from the better signal to noise ratio : the narrower the detection bandwidth, the larger this ratio. Measuring a displacement amplitude of 0.5 Å in a 50 MHz bandwidth requires a sensitivity better than 10^{-4} Å/$\sqrt{\text{Hz}}$. However transient measurements give a larger amount of information in a shorter time. For example, the various types of wave excited by a pulse are readily distinguishable as they travel with different velocities and arrive at distinct times. These transient measurements, useful for the characterization of acousto-electric components, are necessary for acoustic wave excitation by laser pulses and their application to non-destructive testing (5).

This observation led us to modify our compact optical interferometer (6) in order to make it suitable for local measurement of transient mechanical displacements. This entailed replacing the narrow bandwidth electronic circuitry by wide bandwidth circuitry. In this paper, we report our results on impulse responses of bulk and surface piezoelectric transducers and on detection of displacements generated by a laser pulse.

2 - THE PROBE

The main characteristics of the optical heterodyne interferometer previously used to measure coherent displacements are the following : dimensions of the optical part : 8 x 5 x 3 cm^3 + laser He - Ne, operation possible in a vertical or horizontal position, sensitivity : 10^{-4} Å/$\sqrt{\text{Hz}}$, stability : 0.3% for the amplitude, 0.3 degree for the phase. To summarize the principle of operation (figure 1): two beams are extracted (cube BS) from the optical source. The reference beam is directed through a prism towards the photodiode. The probe beam (the frequency of which is shifted by a colinear Bragg cell (f_B)) is reflected by the vibrating sample (f_A), causing a modulation of the beam phase. The beating of the two beams, R and S, on the photodiode results in a phase modulated current at frequency f_B.

The optical system used here differs from the previously described by the addition of a lens. The focussing of the probe beam onto the object has several advantages : defining the spot more precisely, collecting a larger amount of reflected light, making the instrument less sensitive to the tilt of the sample when this is displaced laterally.

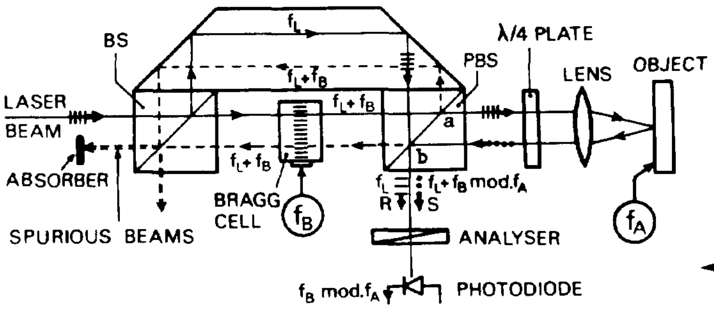


Fig. 1. Optical part of the interferometer. The laser beam is off-centered from the axis of the cubes in order to eliminate the spurious beams reflected at points a and b. BS: beam splitter cube; PBS: polarizing beam splitter cube.

The operation of the probe is improved by off-centering the laser beam from the axis of the two cubes. This off-centering eliminates the spurious signals which come from the reflexions on the splitter interface of the PBS cube. These come on the one hand from the probe beam (point a), on the other hand from the reference beam (point b). These beams, both at the frequency $f_L + f_B$ are prevented from returning to the laser and then from being reflected back to the photodiode.

The large bandwidth processing of the phase-modulated photocurrent is illustrated in figure 2. The output signal of the photodiode is split into two parts. One of these traverses a filter which selects the carrier frequency at f_B and is $\pi/2$ phase-shifted by a cable. The mixing of this component with the other part of the photodector signal gives the acoustic signal at f_A and a signal at $2f_B$. The vibration of the object is recovered by eliminating the high frequency components with a low-pass filter.

The first experiment was the plotting of the mechanical impulse response of a Panametrics transducer of diameter 4 mm having a bandwidth of 15 MHz. The transmitting surface was slightly polished in order to increase its reflectivity and the transducer was excited, through a cable of length 25 cm, by an electric pulse of 60 V and duration 30 ns. The vibration of the surface was examined at points 0.5 mm apart. Figure 3 shows that the entire surface is not active. Although the different zones start to vibrate at the same time, their amplitudes and their damping are not identical. The largest amplitude (20 Å) is at about the centre of the disk. The vibrations of this transducer look strongly damped. Nevertheless this damping is modified if the transducer is fed through a cable having a different length. Supplementary oscillations appear when the transducer and generator impedances are not correctly matched. (7).

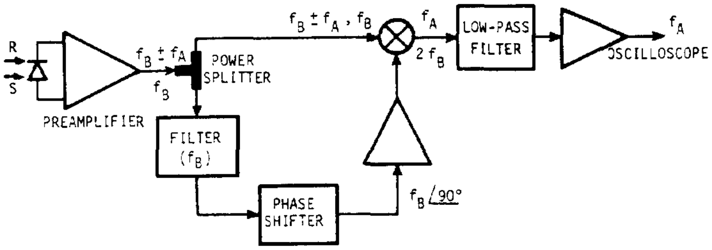


Fig. 2. Wide bandwidth electronic detection circuit. The bandwidth B, less than f_B (70 MHz), is selected by the low-pass output filter.

3 - RESULTS

Three experiments have been performed with this probe in the following configuration :

- Source : standard He-Ne Laser (Power 3mW)
- Detector : PIN photodiode + FET preamplifier (26dB)
- Focussing length : 20 mm
- Bragg cell frequency : f_B = 70 MHz
- Narrow band filter : 70 MHz ± 7 kHz
- Low-pass filter : B = 10 or 50 MHz

The second experiment was carried out with a Rayleigh wave delay line on a $LiNbO_3$ crystal. The probe beam was reflected by the aluminum metallized surface, at 12 mm from the interdigital transducer. Figure 4 gives the probe output signal generated by a pulse (60 V, 20 ns) applied to the tranducer. It demonstrates that the center frequency of this delay line is 17 MHz and that the amplitude of the surface displacement is a little more than 5 Å. With the output filter of bandwidth B = 50 MHz, the minimum detectable displacement is about d_{min} = 0.4 Å. For a mirror like reflecting surface, the probe sensitivity is given by

$$S = \frac{d_{min}}{\sqrt{B}} = 6.10^{-5}\ \text{Å}/\sqrt{\text{Hz}} \qquad (1)$$

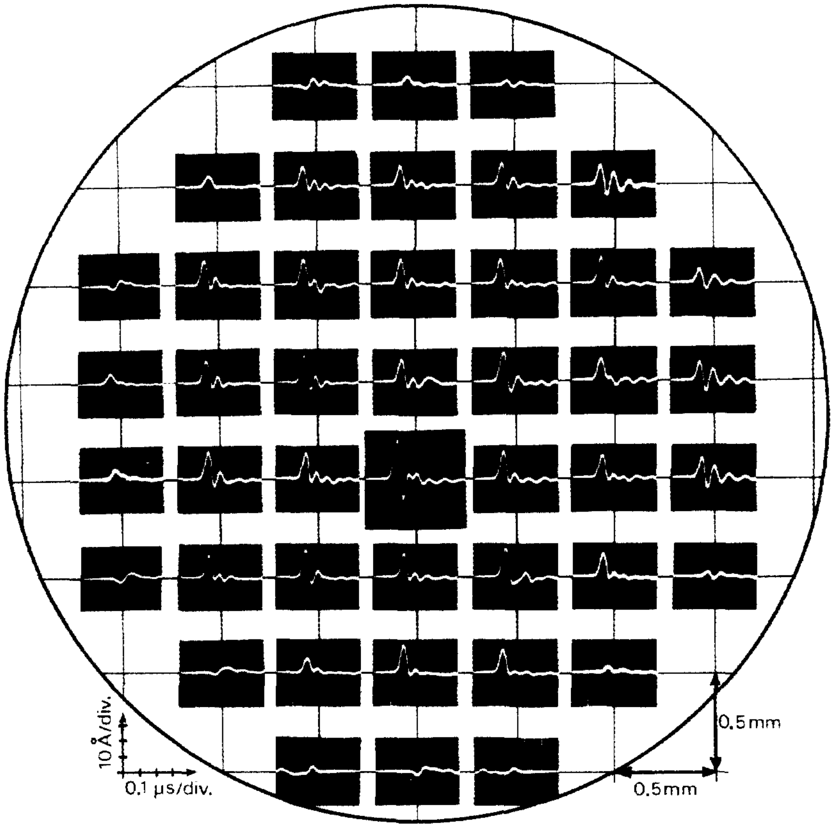
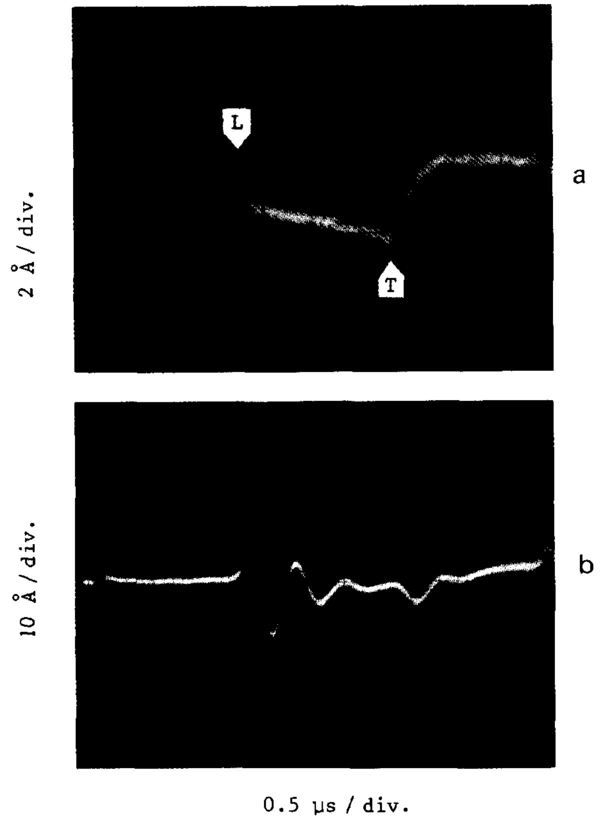


Fig. 3. Local transient vibrations of a bulk wave piezoelectric transducer (f = 15 MHz) excited by an electric pulse of amplitude 60 V and duration 30 ns. The largest mechanical displacement is about 20 Å (detection bandwidth B=50 MHz)

Fig .5. Mechanical displacement of the side of a 10 mm thick plate of aluminum, generated by a YAG laser pulse (5 mJ, 70 ns) striking the opposite side a) bare , b) coated with oil (detection bandwidth B = 10 MHz).



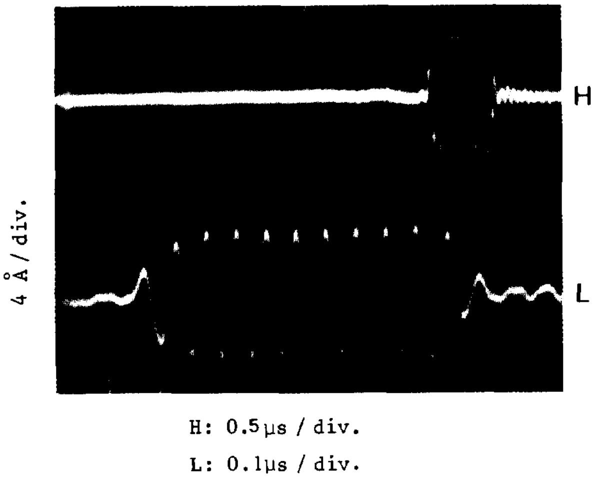


Fig. 4. Response of an interdigital SAW transducer on $LiNbO_3$ substrate (f = 17 MHz) to a pulse of amplitude 60 V and duration 20 ns (detection bandwidth B = 50 MHz).

This value is two times better than the figure reported with the narrow band electronics (6) because here the two side-bands of the phase modulation were detected.

The third experiment refers to the detection of mechanical displacements generated by YAG laser striking a side of a duraluminum plate having a thickness of 10 mm. Figure 5 shows the measured displacement of the opposite side when the excited side is a) bare b) coated with oil. The laser pulse had an energy of 5 mJ and a duration of 70 ns. The shapes of these signals are similar to those observed by other authors (8, 9). The beginning of the signal in figure 5.a corresponds to the arrival of a longitudinal displacement (L), the end to the arrival of a transverse displacement (T). The amplitude of the longitudinal displacement is increased, as shown in figure 5.b, by a factor of 30 dB when the surface is coated with oil

4 - CONCLUSION

This set of three experiments referred to i) the investigation of the transient vibration of the surface of a piezoelectric bulk wave transducer (f = 15 MHz), ii) the recording of the impulse response at a chosen spot on the propagation surface of an IDT surface wave transducer (f = 17 MHz), iii) the plotting of the mechanical displacement of a plate struck by a laser pulse. They demonstrate the adaptability to transient measurements of the optical probe that was originally constructed for measuring coherent mechanical displacements. These transient measurements of a few Angströms performed in a single sweep and with a bandwidth of several tens of MHz correspond to a sensitivity of 5.10^{-5} Å/$\sqrt{Hz}$.

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REFERENCES

1 - W. DÜRR, D.A. SINCLAIR and E.A. ASH, "A high resolution acoustic probe", IEEE Ultrason. Symp. Proc., 594 (1980)

2 - E.P. PAPADAKIS, "Ultrasonic transducer evaluation in five domains : time, space, frequency, surface motion and theory", IEEE Ultrason. Symp. Proc., 104 (1977)

3 - R. ADLER, A. KORPEL and P. DESMARES, "An instrument for making surface waves visible", IEEE Trans. Son. Ultrason., SU-15, 157 (1968)

4 - R.M. De la RUE, R.F. HUMPHRYES, I.M. MASON and E.A. ASH, "Acoustic surface wave amplitude and phase measurements using laser probes", Proc. IEE, 119, 117 (1972).

5 - D.A. HUTCHINS and A.C. TAM, "Pulsed photoacoustic materials characterization", IEEE Trans. Ultrason. Ferroelectrics and Freq. Control, UFFC- 33, 429 (1986)

6 - D. ROYER, E. DIEULESAINT and Y. MARTIN, "Improved version of a polarized beam heterodyne interferometer", IEEE Ultrason. Symp. Proc., 432 (1985)

7 - D. ROYER and E. DIEULESAINT, "Optical probing of the mechanical impulse response of a transducer", Appl. Phys. Lett., (to be published).

8 - D.A. HUTCHINS, R.J. DEWHURST, S.B. PALMER and C.B. SCRUBY, "Laser generation as a standard acoustic source in metals", Appl. Phys. Lett., 38, 677 (1981).

9 - D.A. HUTCHINS and F. NADEAU, "Non contact ultrasonic waveforms in metals using laser generation and interferometric detection", IEEE Ultrason. Symp. Proc., 1175 (1983)

10 - T.E. PARKER, "A new technique for a simple phase-sensitive laser probe", IEEE Ultrason. Symp. Proc., 365 (1974)

11 - H. ENGAN, "Phase sensitive laser probe for high-frequency surface acoustic wave measurements", IEEE Trans. Son. Ultrason., SU-25, 372 (1978).