LASER DETECTION AND IMAGING TECHNIQUES FOR SURFACE EXAMINATION

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ABSTRACT

A coherent laser probe provides the basis for the recording of complex SAW distributions. Using three or more scans, the surface wave velocity can be deduced with an accuracy of a few parts in 10^5. Such measurements are sufficiently sensitive to detect small changes in surface characteristics; as an example, results will be presented on the effect of doping a Si surface. It is also possible to improve the accuracy of the basic elastic constants of the material by reference to the velocity characteristic. Of particular importance is the fact that this technique provides evidence on the effective value of these constants close to a surface; it is, therefore potentially useful for surface layer characterisation.

Surface defects can be detected by means of scattered waves in both the forward as the reverse directions. In principle, either can be used to "image" the defect. Using both these components, the defect size and location can be determined with improved accuracy.

1. INTRODUCTION

The detection of defects using surface acoustic waves is normally based on the observation of scattered waves, using either the transmitting transducer in a receiving mode, or an additional transducer dedicated to the reception role. In most cases, there is a concentration on the *amplitude* of received pulse signals. It is usually difficult to explore many different locations with the transducer(s). To some extent, the limitations of fixed locations can be overcome by resorting to frequency variation - which provides a change in the normalised distances. These effects may, however, be overlaid by the frequency dependence of the scattering function of the defect itself.

An alternative approach is based on the use of cw or pseudo-cw illumination, coupled with the measurement of the *complex* field distribution along one or a number of scan lines. At low frequencies, particularly below about 2MHz, one can hope to obtain a faithful record of such a field distribution using a stylus sensor. However, even at these frequencies, there are great benefits to be derived from the use of a laser probe, acting as a "non-contacting" sensor. Moreover, laser probing techniques can be extended to very high frequencies - our own experiments have reached 150 MHz and stopped there for lack of immediate application, rather than any formidable technical problems. In this paper, we will present some of the techniques of surface characterisation which can be implemented using such a laser probe.

It would be particularly attractive if it were possible to devise a non-contacting source, to complete the inspection system. It is, of course, well known that a high power pulsed electron or laser beam can generate intense acoustic waves; a number of groups are seeking to exploit this phenomenon. The idea has been given further credence recently by the emergence of photoacoustic microscopy {1}, which demonstrated the generation of significant acoust powers in the 0.8 GHz frequency range. The generation of these waves is being studied using a numerical technique for determining temperature and, hence, stress distributions {2}. In the remainder of the paper, we will confine ourselves to a discussion of the laser as a receiving senso

An immediate application of the laser probe is to the evaluation of the velocity characteristic of a surface. The basis of the method will be brief described in section 2, and some recent results are presented in section 3. It turns out that th technique is capable of achieving a very high accuracy - of the order of a few parts in 10^5. This is an improvement by about two orders of magnitude on the precision which can be achieved by computation based on the best available data of materials constants. It suggests that, perhap one might be able to improve our knowledge of these constants by working from SAW velocity data *back* to the constants. This process has been applied to $LiNbO_3$, and the conclusions will also be presented in section 3.

The detection of defects using laser probing techniques involves the evaluation of scattered waves from the defect. One can use these to "image" the defect, if this is sufficiently large. One can, alternatively, as in usual scattering experiments, deduce a great deal of information about the defect without attempting the reconstruction of an image. The basic approa is outlined in section 4, together with some very preliminary results obtained with some simple deliberate "defects".

The potential role for laser probing techniques i NDE is briefly discussed in a final section.

2. LASER PROBE VELOCITY MEASUREMENT TECHNIQUES

The laser probe has evolved over a number of year {3}, {4}. The basic optical and electronic

systems are shown in Figs. 1 and 2.

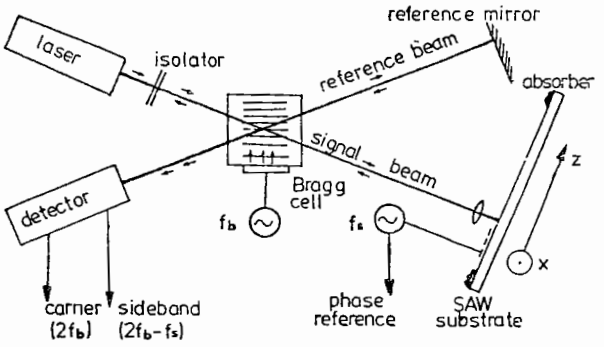


Fig. 1 Schematic of phase sensitive laser probe.

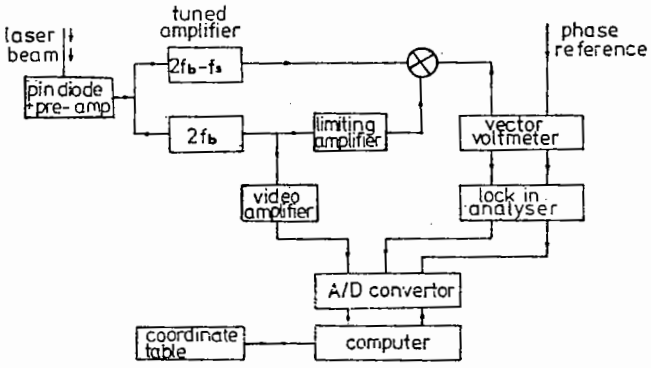


Fig. 2 Block diagram of electronics for recording amplitude and phase of SAW distribution.

The probe is driven by computer controlled stepping motors. It can be positioned with an accuracy of about 1μ, and can measure the phase of the surface wave displacement with an accuracy of about 3^0.

The technique of velocity measurement is based on a comparison of the complex distributions measured along two scan lines, $U_0(x)$ and $U_1(x)$. If the wave vector in a direction making an angle θ to the z axis is $k(\theta)$, we can define the spatial frequency spectrum $f_0(\alpha)$ by

$$f_0(\alpha) = \int U_0(x) e^{j\alpha x} dx$$

$$\alpha \equiv k(\theta) \cos\theta$$

The function $f_1(\alpha)$ relating to the distribution $U_1(x)$ is similarly defined. In the absence of any defects between the scan lines, the amplitude of the spectra differ only by an attenuation constant. However, the phase difference depends on $k(\theta)$; given $f_0(\alpha)$ and $f_1(\alpha)$, the variation $k(\theta)$ can be derived - given only a single value, such as $k(0)$. In this form, the method is, therefore, relative. It can be made absolute by resorting to three rather than two scan lines {4}.

The accuracy which can be obtained by this technique may be limited by the performance of the laser probe, or, by the maximum available size of sample. Under optimum conditions, we have achieved a repeatability accuracy of about $2{:}10^5$. With this precision, one encounters a number of variations in materials which, under normal circumstances, one would regard as beyond reproach. There is, for example, now some evidence that there are variations in the velocity of both quartz and $LiNbO_3$ which are of potential concern to SAW device manufacturers.

The measurement technique works equally well on piezo electric as on non-piezo electric materials. In the latter case, one encounters the problem of transduction. We have solved this in some cases by butt-jointing of a piezo electric material, but, more frequently, by resorting to the liquid coupling technique {5}; indeed, this technique is so simple to use that we now tend to employ it even for piezo electric materials - thereby saving the need for the photolithographic definition of a transducer pattern.

3. VELOCITY MEASUREMENT RESULTS

We have carried out a large number of measurements on $LiNbO_3$ in view of its importance to SAW devices. A particular concern has been the precise curvature in the Z-direction for Y-cut material, as this controls the diffraction rate. Fig. 3 shows a particularly precise result obtained over a range of angles very close to the Z axis.

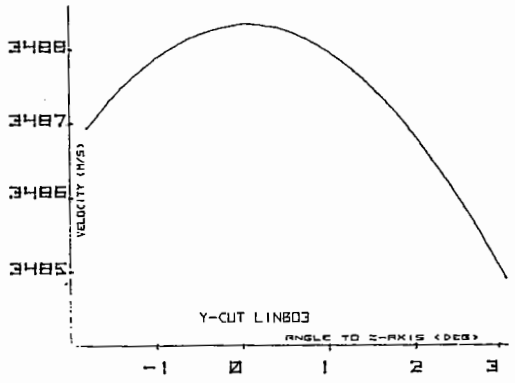


Fig. 3 High resolution velocity measurement for YZ Lithium Niobate.

Fig. 4 shows a result obtained with the liquid coupler on a sample of (111) Si. The experimental result is compared with a computed curve based on book-values of the elastic constants. The maximum deviations here are of the order of $2{:}10^3$ and attributable to the limited accuracy of the elastic constants.

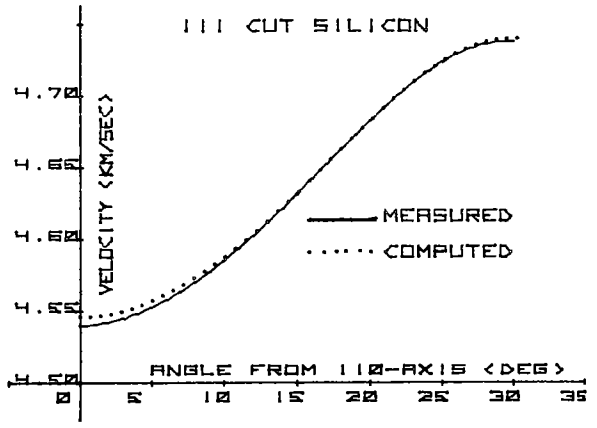


Fig. 4 Measured and theoretical velocity characteristics for (111) silicon

Of greater interest to application is the variation in velocity arising from variations in doping density. Fig. 5 shows the effect of N-type doping on a relatively high resistivity sample of (100) Si. The figure also shows the effect of an oxide layer 0.3μ in thickness. We are embarking on a program to establish the value of this technique for characterising the surface preparation as well as doping levels for Si wafers.

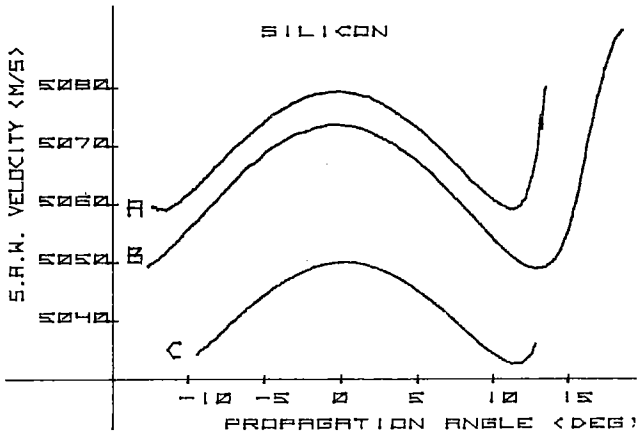


Fig. 5 Effects of surface perturbations on the velocity characteristics of (100) silicon:
a) P type 3 ohm-cm
b) N type 0.01 ohm-cm
c) P type, 3 ohm-cm with 0.3 micron oxide layer

3.1. Deduction of Elastic Constants

The very precise velocity data encourages their use for improving the knowledge of the elastic constants. It is important to appreciate that this technique - if it can be successfully applied - establishes the value of these constants in a thin surface layer. It is, therefore, a technique for measuring the elastic constants of thin films - which it would be almost impossible to establish by the classical techniques.

In attempting to deduce the elastic constants from SAW velocity data, one technique is to obtain a measure of the deviation between the experimental and the calculated curve - for example, by calculating a mean square deviation integral. One can then resort to an optimization method, thereby perturbing the elastic elements until the error integral is minimised. The computation which would be involved in applying this technique directly would be prohibitive. The program we are using - originally devised by Slobodnik, and subsequently modified by P. LaGasse - is efficient but still requires minutes rather than seconds on a large computer for a single curve. We have, therefore, found the gradients of the velocity characteristic with respect to all of the relevant elastic elements by numerical differentiation. We can then use these gradient functions to linearise the optimisation method. This procedure works very satisfactorily. However, there is a more fundamental problem in the fact that the problem appears to be rather unstable in the face of the inevitably finite accuracy of the data and the subsequent computations. We have, therefore, found it necessary to be very selective in the elastic elements which we are seeking to improve. This selection is based on establishing the "strength" of an element - effectively the magnitude of the gradient funtions; further, we define its "effectiveness", being a measure of its potency in reducing the discrepancy between the computed and the experimental data. If we confine our attention to those elements which are both strong and effective, we are able to deduce revised values for the constants which stand up to independent checks. These considerations have led to the following proposed changes:

	SLOBODNIK	% CHANGE
C_{11}	20.3×10^{10} N/m^2	- 2.3
C_{12}	5.3×10^{10}	- 2.4
C_{14}	0.9×10^{10}	-19.0

The effect of using the revised values are indicated in Fig. 6. The result is encouraging - but one is left with an uneasy feeling that, given three parameters to adjust, the mere fact of a fit is, perhaps, less than conclusive. To sharpen the criterion, we then measured the velocity for Y-cut $LiNbO_3$ near the X direction and used the revised elastic elements as tabled above - which have been derived purely on the basis of experimental results near the Z direction.

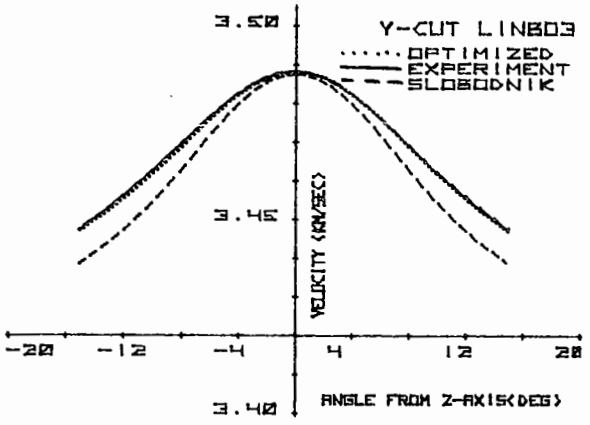


Fig. 6 Experimental, theoretical and optimised velocity curves for Y cut Lithium Niobate over the range ± 15° about Z.

It is seen in Fig. 7 that the improvement in the computed curve is very convincing. We believe, therefore, that the values indicated do represent a distinct improvement on the previously known values.

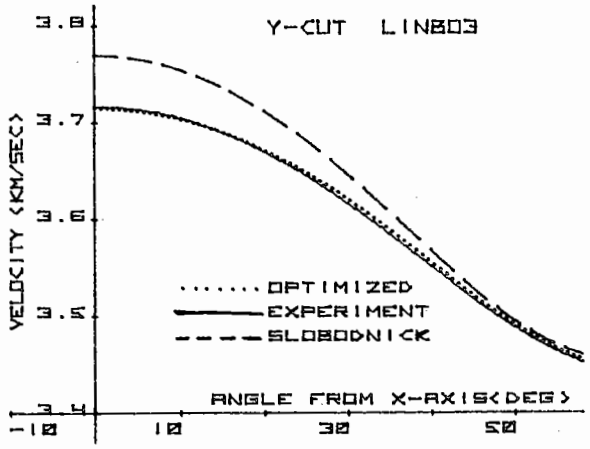


Fig. 7 Comparison between the experimental velocity curve and the computed curve obtained using the revised elastic constants for YX Lithium Niobate.

4. DETECTION AND SIZING OF SURFACE DEFECTS

We can illuminate a surface with a wide beam, and then examine the complex field distribution along a scan line, such as AA', Fig. 8. Given a sufficiently accurate knowledge of the surface wave characteristic, we can then reconstruct the field distribution at smaller values of z. If there is a defect at z_d, a reconstruction at that position will reveal a pattern with much sharper gradients than could arise from the source alone. In principle, this system can, therefore, serve to locate defects, and, if sufficiently large, provide some information on their size. It is worth emphasising that a single scan near the far end of the sample contains all the information required, provided that the signal to noise ratio is sufficiently large, and provided that the density of defects is sufficiently low. Moreover, the search for defects can, to a large extent, be automated; the procedure would be to calculate the field distribution in successive planes, in each looking for amplitude or phase gradients exceeding a prescribed theshhold.

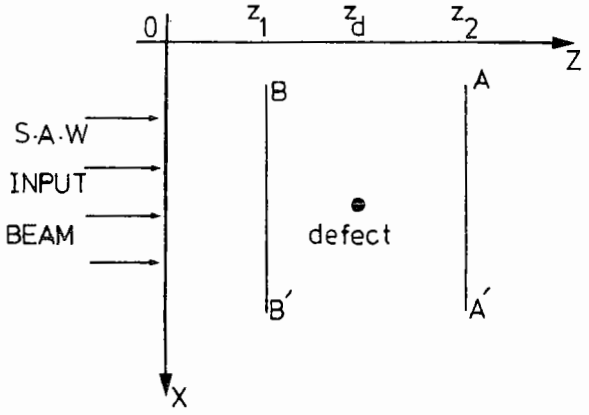


Fig. 8 Recording configuration for defect characterisation.

If, in the first instance, one is content merely to establish whether or not there are any defects, one can avoid the need for the back-propagation altogether. It suffices to record two scans, one at AA', the other at BB'. In the absence of any defects, the spectral density of the two scans would be identical. The probability of a defect between the two scan lines would then be assessed by forming:

$$P = \frac{\int\{f_A(\alpha)f_A^*(\alpha) - f_B\{\alpha)\ f_B^*(\alpha)\}d\alpha}{\int f_A(\alpha)f_A^*(\alpha)d\alpha}$$

The limitation of all these techniques - the smallest detectable defect - lies in the attainable signal to noise ratio as also in the signal to spurious ratio. The former is capable of indefinite improvement, if only by increasing integration times. The latter is more fundamental; for example, reflections from the side of the sample, and the incidence of bulk waves are major sources of difficulty. This suggests that one might be able to effect an improvement in the detection ability if one could, in some way, make a comparison between samples which differ only in the incidence of defects. We have shown, {6} that in principle, this approach can lead to a much greater detection sensitivity. The experiment we conducted was designed to detect a "defect" consisting of a gold dot, 30μ in diameter, and 4000A° in thickness. Fig. 9 shows the distribution along the scan line AA' and 9(b) its backward reconstruction in the plane of the defect - which is clearly not resolved. The comparison with a defect-free sample was effected very simply by removing the gold dot. The complex distribution now measured along AA' was subtracted from the first scan, and the *difference* reconstructed in the plane of the defect, Fig. 9(c). The defect is now clearly resolved.

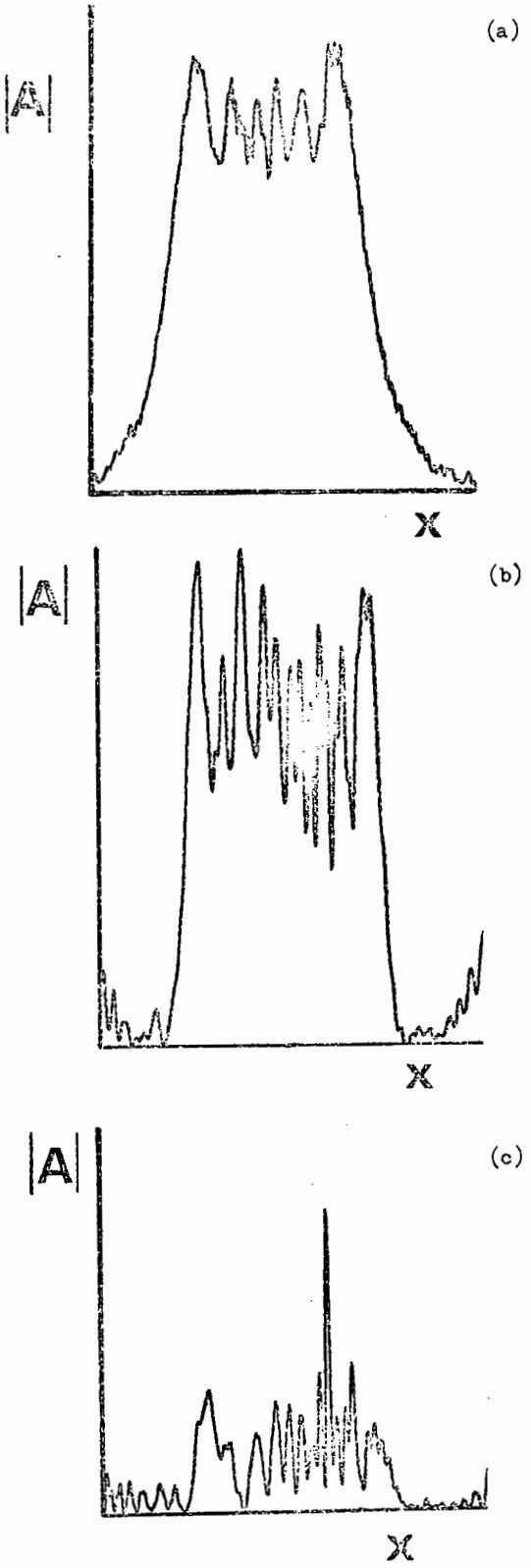


Fig. 9 Reconstruction of defect
(a) Hologram with defect
(b) Reconstruction of (a)
(c) Reconstruction after background subtraction

The experiment as described is somewhat artificial. However, it is possible that with some modifications the basic technique could be used to search for defects in components, given one component known to be defect free. The approach is reminiscent of ultrasonic spectroscopy {7}, where the vibration spectra of components are compared with that of a standard. However, it would obviously be advantageous if it were possible, in some way, to derive the comparison standard from the component under test. These considerations have led us to a somewhat different approach, in which we record *three* scans instead of one which, as we have seen, under idealised circumstances should suffice.

The basic approach is as shown in Fig. 8. The defect is illuminated by an incident wave having a spectrum $I(\alpha)$. In principle, it would be possible to measure this directly by recording the field at $z=0$, if we could devise an attenuating section starting just above $z=0$, and which could wholly absorb the surface wave before it reaches the defect at $z=z_d$. In fact, it is, in practice, not difficult to do this. However, we can avoid the necessity for such a manoeuvre by recording the field at $z=z_1$, z_2 where $z_1 < z_d < z_2$. If the defect extends over a sufficiently small range of z, it will give rise to a perturbation of the incident wave field, which can be rigorously described in terms of a scattered wave spectrum $s(\alpha)$ in the region $z > z_d$, and a reflected wave spectrum $R(\alpha)$ in the region $z < z_d$. If the spectra recorded at $z=0$, z_1, z_2 are $f_{0,1,2}(\alpha)$ we can then write:

$$f_0(\alpha) = I(\alpha) + R(\alpha)$$

$$f_1(\alpha) = I(\alpha)e^{-j\beta(\alpha)z_1} + R(\alpha)e^{j\beta(\alpha)z_1}$$

$$f_2(\alpha) = I(\alpha)e^{-j\beta(\alpha)z_2} + S(\alpha)$$

where we have chosen to define $R(\alpha)$ at $z=0$ and $S(\alpha)$ at $z=z_2$. We can then readily solve the equations for the three spectra. Supressing the α-dependence

$$I = f_0 - \frac{j(f_0 e^{-j\theta_1} - f_1)}{2\sin\theta_1}$$

$$R = \frac{j\, f_0 e^{-j\theta_1} - f_1}{2\sin\theta_1}$$

$$S = f_2 - f_0 e^{-j\theta_2} + \frac{j(f_0 e^{-j(\theta_1+\theta_2)} - f_1 e^{-j\theta_2})}{2\sin\theta_1}$$

$$\theta_{1,2} \equiv \beta(\alpha) z_{1,2}$$

It is at once clear that we must avoid values of z_1 that will make $\sin\theta_1 = 0$. The optimum choice of z_1 depends on the precision of the measurement of distance, the accuracy with which we know $\beta(\alpha)$ and also the range of $\beta(\alpha)$ with which we are concerned. A simple error analysis indicates that the optimum choice is given by $\theta_1 = (n+\frac{1}{2})\pi$ with $n=0$ or 1 in most cases. In some circumstances, it may be advantageous to utilize an additional scan line to reduce the errors when unfavourable values of θ_1 are encountered.

In principle, one would like to make z_2 as large as possible - if only to effect a search for defects over the largest possible region. In practice, one will be limited, as always, by signal to noise considerations but also by the limited accuracy of our knowledge of $\beta(\alpha)$. If we require a phase accuracy of $\delta\phi$ for the scattered spectrum S, we require $\delta\beta\cdot(z_2-z_1) < \delta\phi$. This implies that (z_2-z_1) expressed in the number of wavelengths N, should be limited so that

$$N \leq \left(\frac{\delta\phi}{2\pi}\right)\frac{\beta}{\delta\beta}$$

If the velocity error is only $3{:}10^5$, if $\delta\phi = 0.1$, the maximum value of N is around 500. We see that a very accurate knowledge of the velocity is a prerequisite to the use of these techniques.

As has been pointed out by a number of authors {8}, a knowledge of the scattered spatial spectrum can give a good deal of information about the shape and size of the defect. Varying the frequency over a substantial bandwidth {9}, can provide further information on the depth of a defect. In addition, we must, of course, also establish its location. In principle, one can readily back-propagate the S wave or forward-propagate the R wave. The reconstruction of the field in this way remains valid only up to the defect in each case. If, however, one uses some simple criterion, such as the position of maximum amplitude, it should be possible to estimate the location of the defect.

In the case of a defect which is thin in the Z-direction, both the S and the R reconstruction will provide an image of the defect which, in principle, is as perfect as the limited spatial bandwidth allows. The two reconstructions should be identical at the defect. If, therefore, one were to carry out a correlation between the back-propagated S wave and the forward-propagated R wave, at various positions in z, the correlation should peak at the location of the defect. For such defects as give rise to sensibly similar signal levels in the S and the R waves, this correlation criterion can be expected to provide substantially greater accuracy in the location of z_d.

There is a further technique for locating z_d which we intend to explore. If we measure the spectrum of S at $z=z_2$ at a particular frequency, and then remeasure it at a slightly different frequency, in addition to the large global phase shifts which will be imposed on the spectrum as a whole, there will be a differential phase shift between various angular components of $S(\alpha)$. This differential phase shift is directly indicative of the distance of the source i.e. of the defect. From such a measurement, one can deduce the location of z_d unambiguously in the case of a point defect. In the more general case, the deduction is necessarily less precise - but can be expected to give results with an accuracy comparable to the size of the defect.

4.1. Experimental results

We have carried out a series of experiments on fused quartz substrates, at a frequency of 60 MHz. The waves were launched using the liquid coupler technique. In most of the experiments we made $z_1 = 45\mu$, (i.e. 0.8λ), and $z_2 = 7000\mu$ (i.e. 127λ). We obtained additional control on the angular spectrum of the illuminating wave by restricting the aperture on the substrate using a wax barrier.

In order to obtain some measure of the available dynamic range, we carried out one test without any defect. Fig. 10 shows the result for I, S and R. It is seen that the average level of the spectral density for R and S is about 30 dB below that of I; we should be able to detect scattered waves which exceed this level.

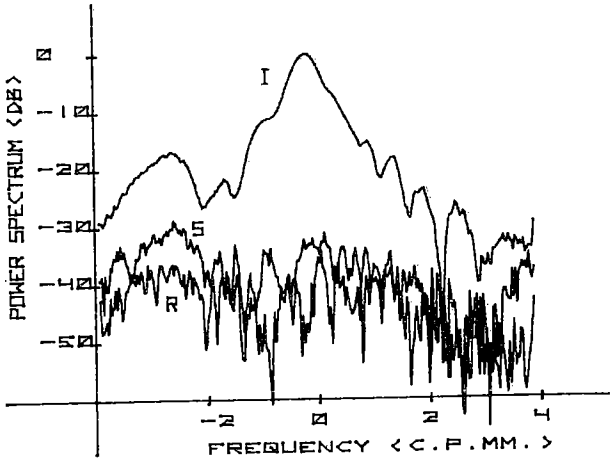
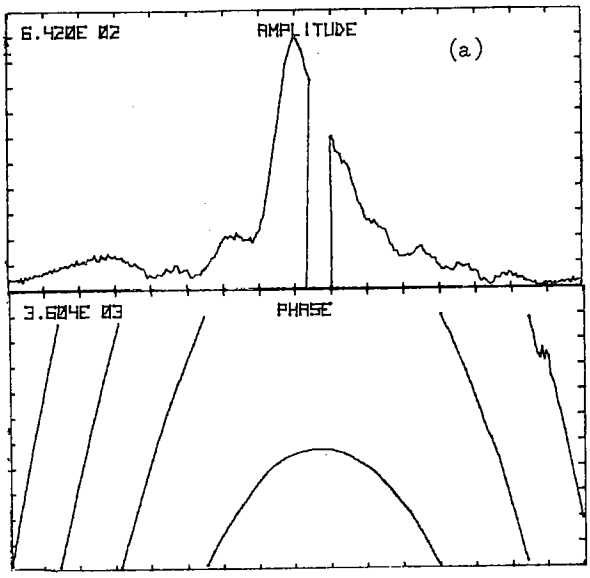


Fig. 10 Determination of I, S and R for a surface with no defect.

As a further test on the method, we took the experimental data which led to Fig. 10 and modified the spatial distribution measured at $z=z_2$ by reducing the amplitude to zero over a distance of 512μ, Fig. 11a. This essentially stimulates a totally absorptive defect located at $z=z_2$. The calculated scattered wave is shown in Fig. 11b. The location of the first zeros accords with expectation for a "defect" of this width.



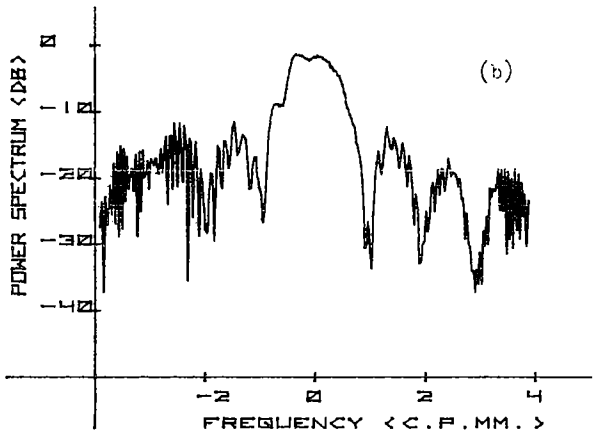


Fig. 11 Sizing of simulated defect
(a) spatial distribution of field just behind defect
(b) the calculated scattered spectrum.

The first physical defect which we have explored consisted of a hole 125μ in depth and 600μ in diameter. The S and R spectra are shown in Fig. 12. Again, the location of the zeros in S are roughly in accord with expectation for a defect of this size.

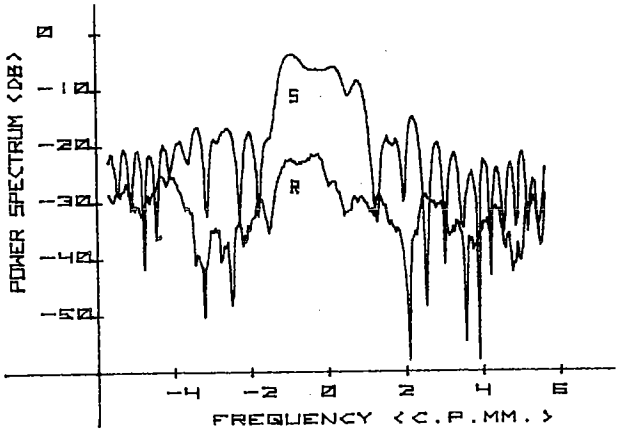


Fig. 12 Sizing of a circular shaped defect.

Finally, we have carried out experiments on a rectangular slot defect (0.5mm x 0.35mm) in both broadside and end-on orientations. The results are shown in Figs. 13 and 14 respectively. In general, the spatial frequency bandwidth corresponding to the main lobes in S and R must equal twice the inverse width of the defect. This predicts the length of the defect in Fig. 13 and the width in 14.

The reflected spectrum in Fig. 13, however, did not provide useful information, as it was within the noise level of our system.

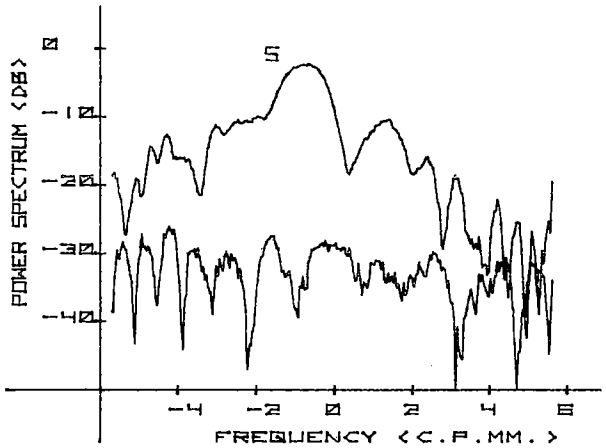


Fig. 13 Length determination of a rectangular slot defect.

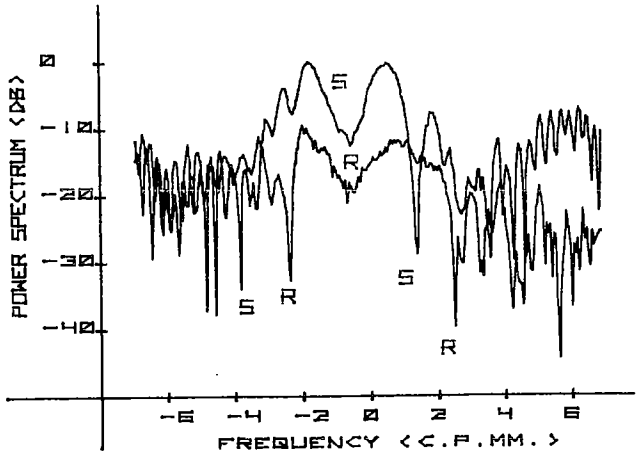


Fig. 14 Width determination of a rectangular slot defect.

CONCLUSIONS

The use of laser probing techniques for precision velocity determination is well established. The accuracy achieved is such that it encourages an extension of the range of applications in three distinct directions. The first is towards surface characterization for both piezo and non-piezo electric materials. Secondly, it leads to an improvement in the determination of elastic constants of materials - a technique which is of unique relevance to the determination of the elastic constants in thin films. Finally, it permits the detection, sizing and location of surface defects.

The examination of this third application is only just beginning but looks very promising. It is immediately clear that the method is effective on highly polished planar samples where high frequency probing is relevant. We believe, however, that the method is also capable of extension to lower frequencies and less idealised surfaces.

ACKNOWLEDGEMENTS

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SUMMARY DISCUSSION

(Eric Ash)

Gordon Kino (Stanford University): Maybe I missed it, but it's impressive that the forward wave scattering - the effect is much larger than the reflection. And it's always very difficult with a straight transducer to make that. What do yo attribute the big effect to?

Eric Ash: We have used rather crude defects. If you imagine a defect as essentially just absorbing everything that hits it and you create a gaping hole in what would have been the forward-going wave, and in our imitation you simply represent this by the negative of the missing amplitude, which would be a larger phase where as if the wave is essentially absorbed and converted into bulk waves. Obviously, a lot of the conversion will be to bulk waves. We don't see that in the reflected wave.

Gordon Kino: But basically you seem to be receiving converging waves?

Eric Ash: Yes. It is quite possible, of course, to calculate the bulk wave loss from the point of entry.

Donald Thompson (Science Center): Do you have a special requirement on the reflectivity on the surface in order to get good pickup?

Eric Ash: The more reflective it is, the better. But just to give you an example, we have done experiments on ordinary smooth, ground stainless steel. We certainly have no problem in doing it on lithium niobate without any metallization, but it's a signal-to-noise issue.

Donald Thompson: I was wondering in particular how bad could the surface be and still have a reasonable signal-to-noise ratio?

Eric Ash: We really haven't tried any experiments with very bad surfaces, but it is a signal-to-noise ratio issue, and we have a great deal of signal-to-noise ratio to spare. There are--I won't go into details--things that we could do to increase the signal-to-noise ratio. If it's too rough, of course, eventually you will start to get

Don Yuhas (Sonoscan, Inc.): What sort of variation do you see in, say, the typical silicon wafers, or silicon? I don't know if it's wafers or not. You described the ten meter per second variation as being due to doping. Did you pick up a handful? What sort of variations?

Eric Ash: I'm afraid we just simply haven't picked up a handful. That's one of the things we wanted to do. We have just done a very small number of experiments so far.

Ed Kraut (Science Center): Eric, I would like to ask you: when you started out your talk, you spoke about lithium niobate and the surface wave loss in lithium niobate. You mentioned the matter of C.I.J.'s, the elastic constants. You didn't say anything about the question of the piezoelectric constants or dielectric constants in lithium niobate which also enter into the surface wave velocity determination. Did you also consider possibilities of errors, small errors, in the piezoelectric constants as well?

Eric Ash: We have tried this. We have looked at the gradients with respect to the piezoelectric constants, and we are convinced they haven't seriously come into what we have done so far. We would like to find them. And we propose to do this by doing essentially delta V over V tests which will isolate them specifically. As far as the dielectric constants are concerned, I don't know whether we have ever calculated that. I think we were rather hoping they were good enough.

Ed Kraut: One other question. The laser technique for velocity measurement on surface waves was used a number of years ago, also, for example, by Eric Lean in studies of harmonic generation on lithium niobate. Could you contrast the -- I don't know what accuracies they were dealing with there, but I would like to ask you what the relative accuracy might have been?

(continued)

Eric Ash: The kind of probe that Eric Lean was using was different in principle because it's a diffraction probe; it has to have a spot size which extends over a number of wavelengths, and I think I'm right in saying that he has used it exclusively for amplitude measurements. But, I mean, you can make the thing phase-sensitive. In contrast, our probe here, we focused to something in the experiments we have been describing as probably less than a tenth of a wavelength. I think it would be very difficult to get the phase accuracy, which is really the fundamental measurement we're making here, using a diffraction probe.

Don Yuhas: There's a detection scheme that's used in acoustic microscopes that works essentially the same way, although the optical detection scheme is quite different. But you can get the same phase accuracy.

Eric Ash: I'm not sure you're going to get the same phase accuracy. You certainly can get the same determination.

Don Yuhas: The spot is focused down to the same size.

George Herrmann (Stanford University): I was wondering whether you used your technique to determine applied stresses quantitatively or whether you think it might be suitable.

Eric Ash: I was intrigued to hear this stuff from yesterday. If one gets the effect of the order of ten to minus four, we should never see them.

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