INTRODUCTION

A new sensor is presented for detecting surface acoustic waves. The sensor constructed, using single mode fiber components, is small and rugged and has better sensitivity (0.0003 Å) than has been reported for other SAW sensors. Optical reflection changes encountered while scanning surfaces can be divided out, making the probe applicable to rough samples of practical interest. Normal surface displacements near a defect (100 μm deep crack) have been measured in both long and short wavelength acoustic regimes.

Optical probing of acoustic waves provides a noncontacting method of making high resolution measurements of the amplitude and phase of surface displacements associated with acoustic waves.\textsuperscript{1-3} We are interested in applications to nondestructive testing where the laser can be placed on an optical bench, but the probe can be used to scan the surface of a sample which may be some distance away. We have developed two fiber-optic interferometric probes for this purpose. Since long lengths of fiber can be placed between the laser and sample without significant losses, large samples can be mechanically scanned with the probe head.

The first fiber probe\textsuperscript{4} is an adaptation of the heterodyne interferometric probe used by De La Rue, et al.\textsuperscript{3} This probe (Fig. 1) is a hybrid containing bulk optic components (mirrors, Bragg cell and lenses), as well as a fiber link. We have found that while scanning is facilitated by the fiber link, alignment of the bulk optic components is still difficult. The first probe has a broadband frequency response which is of use in some applications. However, the filtering
and mixing required for the heterodyne single sideband detection makes the electronics complicated. For these reasons we developed an all-fiber probe with greatly simplified electronics.  

The all-fiber probe (Fig. 2) uses single mode fiber components in place of bulk optic components. The interferometric sensor is insensitive to path length fluctuations resulting from scanning uneven surfaces or from fiber length changes. This insensitivity
results from heterodyne mixing in the detector. This sensor does not need the external mixers, bandpass filters, and power splitters used in the detection electronics of previous length-insensitive SAW sensors.\textsuperscript{2-4} A detailed description of the probe has already been published.\textsuperscript{5} A plot of the response of the probe on a 500 kHz PZT resonator (Fig. 3) shows a dynamic range of 110 dB and a minimum sensitivity of .0003 Å. The best sensitivity reported previously was .002 Å.\textsuperscript{3} The probe can be easily calibrated to give absolute surface displacements in angstroms by noting the signal level where the phase modulator signal peaks.\textsuperscript{5} The frequency response of the probe is given in Fig. 4. Measurements of the frequency response at 34 MHz were obtained on a LiNbO\textsubscript{3} SAW device and agree with theory. Other measurements have been obtained in the range of 19 kHz to 300 MHz.

The all-fiber probe has been incorporated in a computer-controlled scanning system (Fig. 5). The system separately images both optical reflectance and acoustic amplitude and phase. The laser diode is amplitude-modulated with a sinusoidal signal 100 kHz below the acoustic frequency. Hence, the photodiode signal at the surface wave frequency is mixed down to 100 kHz in the detector and a high sensitivity detector and lock-in amplifier can be used. The reflectance signal is obtained from a PZT phase modulator\textsuperscript{5} at 19 kHz. The acoustic and reflectance signals are easily separate with two lock-in amplifiers.

![Graph of output voltage vs. drive power](image)

\textit{Fig. 3.} Dependence of output voltage on acoustic power.
Fig. 4. Frequency dependence of SAW sensor response to a fixed amplitude, variable-frequency surface acoustic wave. Theoretical (solid line) and experimental (circles) results are presented for a 200 m fiber length optical delay along with theoretical results (dashed line) for a 5 m length delay.

The fiber is scanned in two dimensions by dc servomotors with optical shaft encoders. The encoder pulses occur every 500 A of stage displacement giving an overall positioning accuracy of much better than one micrometer.

As an example of the images obtainable with this system, Fig. 6 shows both optical and acoustic images of a focused beam IDT on LiNbO$_3$. A strip of gold is placed over part of the acoustic beam. The acoustic signal is normalized by dividing the optically-detected acoustic signal by the optical reflectance. The acoustic displacement is thus seen to be continuous across the metal boundary.

For applications in nondestructive evaluation, sample surfaces often have considerable surface roughness. Consequently, we examined the probe performance on rough surfaces. Initially, four aluminum samples were examined: a mirror finish, a rolled surface, a machined surface, and a 5 µm grit lapped surface. Figure 7 shows mechanical
stylus measurements of the surface roughness on these samples. Our first attempt at recapturing light in the fiber after reflection from a rough surface is shown in Fig. 8. The fiber was placed near the sample and the light capturing efficiency noted as a function of the fiber-to-sample spacing. Reflection from a specular reflector agrees well with theory. Owing to the small 4µm core diameter of the single mode fiber used, however, the reflected signal decreases rapidly with increasing roughness. The 5 µm finish gave virtually no optical signal in this configuration. It should be noted that single mode fiber is required for stable interferometric sensors.

To increase the amount of scattered light collected while optically probing rough surfaces, Cielo⁷ has found focusing lenses to be quite effective. A probe head using two microscope objectives (Fig. 9) was assembled. The top objective collimates the light emitted from the fiber. The lower objective can be changed depending on the roughness of the sample and the optical definition required. Larger power objectives give a smaller optical spot size yielding better results on rough surfaces;⁷ however, depth of field is impaired, making sample flatness and alignment more critical.
Fig. 6. Reflectance normalization by SAW sensor. (a) Optical image of gold strip on LiNbO₃. (b) Amplitude image of an acoustic beam over the gold interface. Acoustic amplitude is continuous across the interface. Image dimensions are 1 mm x 1 mm.
Fig. 7. Mechanical stylus measurements of surface roughness. (a) Aluminum front surface mirror, (b) Machined aluminum. (c) Rolled aluminum. (d) 5 \( \mu \text{m} \) grit lapped aluminum.

The lens system also provides a larger working distance between the sample and the optics, as well as making the tilt of the surface less critical. Using the lens system and the reflection normalization scheme, rough surfaces were examined with the laser probe. Figure 10 shows results on the 5 \( \mu \text{m} \) lapped finish described previously. The acoustic signal measured was the amplitude times the cosine of the phase angle. The unnormalized acoustic signal (Fig. 10a) has an envelope corresponding to the acoustic signal; however, there is a large amount of "noise" from reflectance changes encountered while scanning the surface. The reflectance (Fig. 10b) measured at the phase modulator frequency is seen to vary over a range of more than 10:1. However, by dividing the two signals and throwing out any points with a reflectance less than a chosen threshold value, the true acoustic signal is recovered (Fig. 10c). This demonstrates that the probe can make quantitative measurements of surface displacements on rough surfaces of practical interest. Surfaces with peak roughnesses up to 12 \( \mu \text{m} \) have been successfully
Fig. 8. Optical power re-entering fiber after reflection. Fraunhofer diffraction theory for specular reflector (solid line), aluminum front surface mirror (circles), machined aluminum (triangles), and rolled aluminum (squares).

Fig. 9. Focusing lens system. Upper 10 x objective collimates beam. Lower objective focuses to a small spot on the sample.
measured with the probe. Comparing this performance with typical roughnesses produced by common manufacturing processes\(^8\) shows the probe should work well on surfaces prepared by drilling, milling and grinding. Difficulties would be encountered for rougher surfaces prepared, for example, by sandcasting.

We next examined the ability of the probe to detect defects in materials. An EDM crack 1.5 mm x 50 μm x 100 μm deep was spark-cut in an aluminum test sample. This defect was then examined at two
acoustic frequencies (10.5 MHz and 1.5 MHz) using edge-bonded surface wave transducers. The defect was clearly imaged in both cases.

At 10.5 MHz the acoustic wave number k and the defect depth a give a ka product of 2.0. In this short wavelength regime, the acoustic displacements near the defect are shown in Fig. 11. The displacement near the defect is seen to increase and the reflected wave gives rise to standing waves in front of the crack. Most of the wave is reflected by the defect so the amplitude behind the crack is quite small.

In the long wavelength regime, at 1.5 MHz, the ka product is 0.3. In this case (Fig. 12), the defect only slightly perturbs the surface wave. The acoustic amplitude increases symmetrically on both sides of the defect. Fig. 13 shows a two-dimensional perspective view of the defect at 1.5 MHz. We are currently examining the problem of determining the crack dimensions from the near-field acoustic amplitude distribution surrounding the defect.

Acoustic pulse-echo measurements were also made of the defect using the same transducers. At 10.5 MHz, the defect produced a strong echo. However, at 1.5 MHz, the defect produced little, if any, discernable signal. The laser probe thus gives quantitative information about a defect in a frequency range where pulse echo measurements have difficulty detecting the presence of the same flaw.

The laser probe has been found to be a very versatile laboratory instrument. We have done work on characterizing loss mechanisms in high-frequency SAW devices. In addition, transducer surface displacements have been measured and compared with theory. This information should help in the design of more efficient transducers.

In future work, we plan to continue to characterize defects from the near-field amplitude information obtained by the probe. On rough surfaces, by expanding the optical beam, it may be possible to optically average the surface reflectance changes. In this way, the electronic division requirements placed on the system will be reduced. Finally, we are considering totally noncontacting systems to measure surface displacements. By heating the sample with a modulated high-power laser beam to produce thermal expansions, no contacting mechanical transducer would be required.

In conclusion, we have developed an all-fiber-optic surface wave probe with better sensitivity than any previously reported. The probe is able to compensate for surface reflectance changes encountered while scanning rough surfaces. This makes the probe applicable to rough samples of practical interest. Finally, we have obtained near-field acoustic images of defects in both long and short wavelength regimes.
Fig. 11. Acoustic amplitude scans around a defect. Short wavelength regime 10.5 MHz, $ka = 2.0$. (a) Long scan across center of crack. (b) Magnified scan across center of crack. (c) Scan parallel to crack (front). (d) Scan parallel to crack (behind).
Fig. 12. Acoustic amplitude around defect. Long wavelength regime 1.5 MHz, $ka = 0.3$. (a) Across crack. 3 mm scan. (b) Parallel to crack. 2.4 mm scan.

ACKNOWLEDGEMENT

The authors wish to thank W. Hipkiss and S. Bennett for their help in the design of the automated scanning system. This work was sponsored by the Center for Advanced Nondestructive Evaluation, operated by the Ames Laboratory, USDOE, for the Air Force Wright Aeronautical Laboratories/Materials Laboratory and the Defense Advanced Research Projects Agency under Contract No. W-7405-ENG-82 with Iowa State University.

REFERENCES

Fig. 13. Image of crack in aluminum test sample. 1.5 MHz, $ka = 0.3$. Defect is 1.5 mm wide and 0.1 mm deep. Transducer is to the left.


DISCUSSION

H.N.G. Wadley (National Bureau of Standards): I wonder what the physical constraints are that limit the bandwidths of the device, especially at the lower frequency end?

R. Jungerman (Stanford University): It is basically the fiber length. If you make a longer fiber loop, you can extend the frequency response to lower frequencies, although practically speaking, it is probably limited to a few kilohertz, say. For the thermal displacement microscope work, you may want to develop some different probing technique which would be applicable to quite low frequencies which are of interest there.
B.B. Djordjevic (Martin Marietta): When you extend bandwidths, you're implying really broad bandwidths, but I think that's a little narrow. You're always operating at very narrow bandwidths. You can cover a long range of frequency by readjusting your lock-in amplifiers, but if you would have a multifrequency mode wave, you will only be picking one component, at least that's how it looks from your schematics. If you would have an impulse on a surface wave travelling in front of your probe with multifrequency components, you could know the results of all those components, couldn't you?

R. Jungerman: As I showed in that one schematic, there is a cosine squared curve which is a frequency response, so if we looked at an acoustic wave in a pulse mode, we'd have to divide out by that frequency response of the probe itself. This is not flat, but it does cover a large frequency range.

B.B. Djordjevic: And then integrate with time?

R. Jungerman: Yes.

G.S. Kino (Stanford University): It is a matter of swapping sensitivity for bandwidth, really. You can do it that way or, comparatively, you can swap sensitivity.

F. Muennemann (Stanford University): You claim displacement sensitivity fractions of Angstroms, which seems to be almost a nuclear scale. Is that real? Can you comment on what it means to be looking at displacements that are that small?

R. Jungerman: I alluded to that briefly. Yes, I claim $3 \times 10^{-4}$ Angstroms, but that is still about the diameter of a nucleus, so what we are looking at is a dynamic displacement averaged over the optical beam. So even though you can say the atoms were mounting up and down the scale of perhaps an Angstrom or so, if you average over the large optical beam you can get an average surface position. We are looking at the dynamic component of that displacement at the measurement frequency. It is a bit difficult to take it to begin with, but you can actually consider that your ear is sensitive to similar displacements when you are hearing very soft sounds.