case, for an aperture of 100 wavelengths; the loss will be smaller for a narrower aperture. It seems that a reasonable upper figure for the contribution to the insertion loss from non-standard irradiation of the output transducer may be as much as 1.3 dB.

Richardson and Kino (8) used a path-length of 3.05 cm and an aperture of 38 wavelengths. The value of $\varphi$ is reduced by a factor of 38/100, as compared with the value of 1.097 used in Section IV. The insertion loss for $0.1^\circ$ tilt is then found to be 0.063 dB, and the insertion loss for misalignment due to a 0.1$^\circ$ divergence of the beam direction from the line joining the center-points of the two transducers is found to be 0.384 dB. From Fig. 3 of Richardson’s and Kino’s paper, $a/l$ and $b/l$ can be taken as 0.2, and bearing in mind that there is little contribution to the loss from the amplitude and phase ripples, Eqs. (17) and (18) give a contribution to $E$ of 0.294 dB. The loss due to power in the side lobes is about 0.1 dB, according to observations by Richardson and Kino (8), Kharusi and Farnell (12), and Williamson (private communication). The predicted loss due to inefficiency is thus about 0.85 dB, and the error in the calculation, due to the ideal forms of the various defects that were assumed to simplify the calculation, is probably substantially less than 0.1 dB. The loss observed by Richardson and Kino and not accounted for was about 0.9 ± 0.2 dB. The agreement is good, and it appears that the effects discussed in this paper can account for the residual observed losses not previously accounted for.

These residual losses do not form part of the transmission coefficient $T$, but contribute to the efficiency factor $E$. Only $T$ can be affected by an electrical network connected between the transducer and the load. Thus the residual losses cannot be reduced by changing the parameters of such a circuit.

REFERENCES


Holographic Interferometry Applied to Motion Studies of Ultrasonic Bonders

ALAN D. WILSON, BYRON D. MARTIN, AND DOUGLAS H. STROPE

Abstract—Time-average holographic interferometry is used to determine the complicated motion of ultrasonic wire bonding devices resonant near 60 kHz. Typical bonder motions of 2.5 micrometers (100 microrches) are easily observed within an accuracy of 5% or better. Discussion of the measurement principle is given, including the optical techniques used to determine the various bonder motions. Holographically measured longitudinal, rotational, and flexural motions are illustrated by showing and interpreting representative fringe patterns (photographs taken of the holographic image). The holographic technique clearly identifies the nodal regions on the bonding tool and on the horn. Peculiar rotational or twisting behavior of the horn is shown. The effects of asymmetric loading of the tool are dramatically revealed by the holographic technique. Examples are used to illustrate the use-
fulness of the time-average holographic interferometry technique in determining the characteristics of a complicated bonding system.

**INTRODUCTION**

Ultrasonic bonding techniques have been used for some time on the semiconductor electronics industry for interconnection joining. In order to produce highly reliable ultrasonic bonds with pull strengths approaching the ultimate tensile strength of the bonding wire, it is necessary to fully characterize the bonding device. Such characterization is usually quite complicated. The maximum motions produced by the bonder are generally less than 5 microns (200 microinches) at a frequency of 40 to 80 KHz. Because of the shape of the bonding tip and other components, these motions are not easily probed by commonly used proximity sensors. Furthermore, the bonders usually do not lend themselves to traditional vibration nodal analysis by Chladni particle techniques.

Time-average holographic interferometry is well suited for analyzing ultrasonic bonders because it is a measuring technique which:

1. does not load the object being studied,
2. responds to the vector displacement of the object,
3. has a resolution of less than 10 microinches,
4. is essentially independent of object vibrating frequency for a single sinusoidal motion,
5. provides a single complete “picture” of the object motion without spatial scanning of the object,
6. clearly determines the location of nodes.

The purpose of this paper is to present some experimental results obtained with a commercial ultrasonic bonder; the data illustrates the type of motion expected from such a device.

**EXPERIMENTAL**

The ultrasonic bonding device (Manufactured by Sonobond Corp., West Chester, Pa.) investigated (Fig. 1) consists of a magnetostrictive transducer, a quarter wavelength stub, a velocity transformer or “horn,” and the bonding tip. This active unit is mounted in a collet clamp (Fig. 2). A movable stage on which specimens are mounted for bonding is also evident in Fig. 2. Resonance of the bonding device occurs near a frequency of 60 kHz. The device was driven by a 20 watt power supply (Manufactured by UTI, Mountain View, California).

The experimental arrangement used to make the holograms is shown in Fig. 3. Figure 3a illustrates the technique for studying the motion of the bonding tip, and Fig. 3b depicts the technique used to examine the horn motion (with and without a bonding tip). Exposure times of Eastman Kodak 649-F (Manufactured by Eastman Kodak Co., Rochester, N.Y.) emulsion in Fig. 3 are approximately 20 seconds. A slight variation of Fig. 3a is used to obtain holograms of bonder motion during bonding. In this case Agfa-Gevaert 14C70 and 10E70 (Manufactured by Agfa-Gevaert Inc., Teterboro, N.J.) emulsions are used.

To make a hologram of the entire bonder or of the tip vibrating in air, the resonant frequency of the system has to be determined; this can be done by any one of a number of techniques: transducer current-voltage characteristic versus frequency, fiber optic proximity displacement sensor, real-time holography, and laser interferometry. Once the resonant frequency is established, the device is operated continuously.
RESULTS

Data representative of that obtained with a tungsten bonding tool are shown in Fig. 4. Using the configuration of Fig. 3a, holograms are made of a tungsten bonding tool, 0.160 cm (1/16 inch) in diameter and 2.2 cm (0.87 inch) long, mounted in a Sonobond horn-transducer assembly (Manufactured by Sonobond Corp., West Chester, Pa.) with a 1.25 cm (0.50 inch) extension of the bonding tool tip beyond the lower horn edge. Fig. 4a shows the tool in its rest or static state. The end of the cap screw which clamps the tool to the horn is visible about one-third of the way down the bonding tool. Figures 4b, 4c and 4d show the tool at a resonant frequency of approximately 60 kHz as the power is increased. The brightest fringe, a nodal point, is located about three-fourths of the way down the bonding tool (see the arrow in Fig. 4d). The location of this fringe does not change as the power to the transducer is altered; this is seen by comparing Figs. 4b through 4d.

Another node occurs on the opposite end of the bonding tip and is located just above the horn. Again, it appears as a bright fringe because of the time-averaging process. In time-average holography of a vibrating object, nodal regions (zero motion points) are easily identified as the brightest point.

The bonding tool used in this study has a sapphire insert which engages the wire. As seen in Fig. 4, no fringes are evident on the sapphire insert. This was due to the insert being loose in the tool. Although there was no static looseness observable, this problem manifested itself at 60 kHz. The principal motion of the tool is flexing in a plane perpendicular to the page and along the axis of the tool. However, because of the slight diagonal fringe, it is evident that the tool is twisting slightly along the longitudinal axis. Figure 5 shows the tool displacement versus position for the image of Fig. 4d.

Next, the velocity transformer or horn is examined. This section is designed to be a quarter wavelength section and, because of its tapered shape, acts as an amplifier. The horn, with and without a bonding tool, is examined holographically using the configuration of Fig. 3b. The horn viewed from its side and illuminated from the end is shown in Fig. 6 with the bonding tool in place. Figure 6a shows the horn in its static state. Note the uniform illumination of the horn. Figure 6b is the horn at resonance and is oriented exactly as that in Fig. 6a, where the bonding tool lies in a plane parallel to the page. Note the strange shape of the bright fringe nodal region near the center of the horn. Figure 6c is another view, with the horn rotated 30° in its clamp, so that the top of the bonding tool is now pointing out of the page (the bottom of the tool is pointing into the page). Note the change in the characteristics of the fringe pattern. Figure 6d is another 30° rotation, and the shadow cast by the tool is visible. The nodal area is now better defined. Figure 6e is 90° rotation (with respect to Figs. 6a and 6b); now the bonding tool is perpendicular to the page. Note how narrow the nodal area now appears. Figures 6f through 6m are successive views with progressive 30° rotations. Of particular interest is the difference in the characteristics of Figs. 6e and 6k; in both of these the bonding tool is perpendicular to the page, but the views show opposite "sides" of the horn. (This will be discussed later in the paper.) In Fig. 6e the nodal area is localized to a smaller region than in Fig. 6k.

A somewhat similar series of pictures were obtained without a bonding tool (Fig. 7). Here the horn is oriented in such a direction that, if the tool were in place, it would lie in the plane of the page. Comparison of the series with Fig. 6b proves interesting. In Fig. 7a, for example, note the diagonal fringes near the free end of the horn. These are due to a rotation of
Figure 6. Ultrasonic Bonding Horn with Tool in Place. (a) Static. (b)-(m) Vibrating and Viewed Starting at 0° and Increased in 30° Steps up to 330°.
Figure 6. Continued.
Figure 7. Ultrasonic Bonding Horn. (a) 0° View. (b)–(i) Angle of View Increased by 45° Steps up to 360°.
The very bright fringe appears adjacent to the wire feed hole. This is again the node on the horn. The remaining figures in Fig. 7 are successive views taken every 45° around the horn. 

Figure 7i should be compared to Fig. 7a, 360° and 0° views, respectively. The comparison shows that the clamping conditions repeat themselves sufficiently well in that these holograms are identical. The transducer-horn assembly was rotated in the transducer clamp to obtain these views.

From Figs. 6 and 7 it can be seen that the motion of the horn is significantly different with and without the bonding tool attached.

The final result is that obtained for a bonding tool during bonding. In this case, the bonding tool has a flat blunt chisel shape. To show the effects of eccentric tool loading, holograms during bonding were made under two different conditions—with the wire under the tip to the right of the tool center axis, and again to the left of the axis. The exposure is initiated about 100 milliseconds after the bond commences and lasts for approximately 125 milliseconds. Agfa-Gevaert 14C70 emulsion is used because of its high sensitivity to He-Ne radiation, a characteristic required because of the desired short time-average exposure time. There is, however, some loss in image quality because of image noise and resolution limitations (as compared to higher resolution emulsions). Figure 8a shows the bonding tool vibrating freely in air; Fig. 8b the tool with the wire engaged on the left side of the tool center; and Fig. 8c with the wire engaged on the right side of the center. In Fig. 8a two nodes are visible on the tool below the horn. These nodes are slightly diagonal, indicating that there is a slight rotation about the vertical axis. Figures 8b and 8c exhibit large amounts of rotation about the vertical axis caused by the off-center loading. The nodes are no longer perpendicular to the tool axis but show the general trend of the motion—flexing and twisting. In this series of photos the bonding horn is just visible at the top, and the test wire and anvil are visible in the lower portion. It should be noted that the bonding tool used in Fig. 8 is extended a different length below the horn than the one in Fig. 4.

DISCUSSION

Fringe Formation

To interpret the fringes of Figs. 4, 6, 7, and 8, it is necessary to discuss briefly the formation of fringes in hologram interferometry and, in particular, the formation of fringes in time-average holography.

In hologram interferometry, the wavefront phase change at a point is given by

$$\Delta \phi = \frac{2\pi}{\lambda} d \cdot (1 + \hat{f}).$$

Light is reflected or scattered from a general diffuse surface that is perturbed in some manner such that a point experiences a vector displacement $d$. The vector $\hat{f}$ points toward the illuminating source, and the light is scattered to viewer in the direction $\hat{f}$. The hologram allows the wavefront corresponding to an unperturbed state to be recalled and compared with the wavefront of the perturbed state. In Fig. 4 the direction of
illumination and view are principally along the direction of the object displacement (purposely arranged this way), and thus a fringe corresponds to the phase change

\[ \Delta \phi = \frac{4\pi}{\lambda} d_n \]  
\[ (2) \]

where \( d_n \) is the normal component of the displacement. For Figs. 6 and 7, the direction of illumination is in the direction of longitudinal displacement, but the direction of viewing is perpendicular to the displacement direction. Thus, for small longitudinal displacements, the following equation holds:

\[ \Delta \phi = \frac{2\pi}{\lambda} d_l \]  
\[ (3) \]

where \( d_l \) is the longitudinal displacement.

Other motions besides longitudinal are present in Figs. 6 and 7. For example, there is a flexural motion and a rotational mode about the longitudinal axis of the horn. For the flexural motion, the equation of the phase is

\[ \Delta \phi = \frac{2\pi}{\lambda} d_f \]  
\[ (4) \]

where \( d_f \) is the component of flexural motion in the plane perpendicular to the page. For the rotational mode, the phase equation is given by\(^6\)

\[ \Delta \phi = \frac{2\pi \alpha}{\lambda} \rho \sin \gamma \]  
\[ (5) \]

where \( \alpha \) is the angle of rotation, \( \rho \) is the radius of the circular object (i.e., the horn) at any cross-section, and \( \gamma \) is the angular coordinate of the point in question on the object.

From the above expressions it is apparent that the viewing and illumination directions and the relative direction of the displacement determine the basic relation between a fringe and the causing displacement. For example, the sensitivity in the end illumination of the horn with side viewing is one-half that of normal illumination and viewing of the bonding tool (Fig. 4). This illustrates the necessity of specifying the pertinent directions.

Time-average holography of a sinusoidally vibrating object complicates the problem because the dark fringes are the roots of the zero order Bessel function of the first kind. That is, dark fringes occur when

\[ J_0(\Delta \phi) = 0. \]  
\[ (6) \]

Likewise bright fringes occur when \( J_0(\Delta \phi) \) is a maximum or a minimum. Table I tabulates fringe number and corresponding displacement for the motions expected for the viewing and illuminating configurations employed here.

To obtain the angle of rotation (for example, of the horn tip, Fig. 7a) the fringe order is first determined for the rotational motion, and then the Bessel function root is determined from Table I. This will give the maximum value for \( \Delta \phi \) to be used in Eq. 5 for obtaining the rotation angle. Alternatively, the angle of rotation is equal to the fringe frequency, defined as the root of \( J_0 \) corresponding to the fringe order divided by \( 2\pi \) times the object radius normalized with respect to the wavelength. The fringe order is established by counting from the center of the cylindrical object to the projected edge.

**Object Behavior**

The fringes of Figs. 6 and 7 are troublesome due to the changing character of the node in Fig. 6. The explanation of the fringe system, including the nodal area, lies in the fact that there are three superimposed motions going on simultaneously, namely longitudinal, rotational, and flexural motions. For Figs. 6 and 7, fringes which run around the horn like a band are due to either longitudinal or flexural or the sum of the two motions. The axial fringes and axial components are the result of rotational motion. The total fringe systems are therefore the result of mode combinations. Mode combinations have previously been studied.\(^7\)-\(^9\) Insufficient data are available to completely interpret the fringe patterns. For example, Wilson\(^9\) has shown that the relative phase of rationally related combinational modes is a most important parameter and drastically affects the appearance of the fringe system. The phases and frequency relationships were not measured when the holograms of the bonder were made. It is questionable whether it could have been determined. However, it is probable that the combining modes are of the same frequency. When the plane of the bonding tool is parallel to the page (i.e., Figs. 6b and 6h), then the fringes are generally made up of longitudinal and rotational motions. This is because the loading of the horn by the tool is such that the flexural vibrations for Figs. 6b and 6h are in the plane of the page. The illumination and viewing directions make the holographic setup less sensitive to these motions while remaining sensitive to the longitudinal and rotational motions. For views 90° away from this condition (for example, Figs. 6c and 6k), the holographic interferometer is now sensitive to all three motions because of the orientation of the tool with respect to the illumination and

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<th>( a ) in</th>
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\[ J_0 \] is the root of \( J_0 \) corresponding to the fringe order.
Annular Piezoelectric Surface Waves

CLIFFORD K. DAY, MEMBER, IEEE, AND GEORGE G. KOERBER, SENIOR MEMBER, IEEE

Abstract—This article presents a formal solution of the boundary value problem pertaining to annular piezoelectric surface waves propagating upon a transversely isotropic substrate. Phase velocity, decay constants and amplitude ratios are computed for a PZT-5A substrate. The theoretical phase velocity agrees well with that determined experimentally.

INTRODUCTION

The use of piezoelectric surface waves for microwave signal processing has recently evolved into a full-fledged technology. This technology is based in part upon theoretical analyses of straight-crested piezoelectric surface waves upon an infinite, planar piezoelectric substrate. References 1–5 are typical examples of such studies.