Two-Dimensional Arrays for Medical Ultrasound Using Multilayer Flexible Circuit Interconnection

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Abstract—The development of 2-D array transducers has received much recent interest. Unfortunately, fabrication of high density 2-D arrays is difficult due to the large number of electrical interconnections which must be made to the back side of the elements. A typical array operating at 2.2 MHz may have 256 or more connections within a 16.4 mm circular footprint. Interconnection becomes even more challenging as operating frequencies increase. To solve this problem, we have developed a multilayer flexible (MLF) circuit interconnect consisting of a polyimide dielectric with inter-laminar vias routing signals vertically and etched metal traces routing signals horizontally. A transducer is fabricated from an MLF by bonding a PZT chip to its surface and dicing the chip into individual elements, with the saw kerf extending partially into the top polyimide layer to ensure physical and electrical isolation of the elements. The KLM model was used to compare the performance of an MLF 2-D array to a conventional hand wired 2-D array. MLF and wire guide transducers were fabricated, each with 256 active elements, 0.4 mm interelement spacing, and 2.2 MHz center frequency. Vector impedance, pulse length, bandwidth, angular response, and cross-coupling were found to be comparable in both types of arrays. Using the MLF, however, fabrication time was reduced dramatically. More importantly, MLF technology may be used to increase 2-D array connection density beyond the limitations of current hand wired fabrication techniques. Thus MLF circuits provide a means for the interconnection of current and future high frequency 2-D arrays.

I. INTRODUCTION

Innovation in transducer design has made possible many advances in ultrasonic imaging technology. The progression from piston transducers to multidimensional arrays has been accompanied by an increased level of sophistication and system complexity. Improvements have been made in backings, matching layers, and transducer materials, yielding broadband arrays with excellent imaging characteristics. Transducers for high-end ultrasound scanners employ over 200 elements and have −6 dB fractional bandwidths around 80%. These transducers may be 1-D arrays or 1.5-D arrays consisting of several rows of elements (e.g., 3 × 85). The introduction of 1.5-D arrays has made possible rudimentary dynamic elevation focusing and phase aberration correction algorithms to reduce B-scan slice thickness. However, the elevation spatial sampling of 1.5-D arrays may not be adequate for useful elevation phase correction [1]. True 2-D arrays are necessary for improved 2-D focusing, high-speed volumetric scanning [2], for most 2-D phase correction methods [3], [4], and for 3-D angle independent flow imaging [5].

The development of 2-D arrays has been limited by fabrication difficulties due to the high density of electrical interconnections. A fully sampled 2-D array with a 16.4 mm diameter circular aperture, 0.4 mm pitch, and 2.2 MHz center frequency would have $(41)^2(\pi/4) = 1320$ elements, each of which would require an independent electrical connection. Although sparse array designs [6], [7] may be used to reduce the number of connected elements, interconnection is still a challenge.

Various interconnection schemes for 2-D arrays have been investigated. Since 1986 we have successfully employed a technique for the fabrication of 2-D arrays in which the elements of the array are hand-wired from an epoxy wire guide to an external connector [8]. The wiring is embedded in an epoxy matrix which serves as the transducer backing. Using this technique, we have fabricated 3.5 MHz arrays of up to $40 \times 40 = 1600$ elements with 440 active elements at 350 µm pitches [9]. Unfortunately, hand wiring is extremely labor intensive, requiring approximately 6 weeks to fabricate each array. This makes empirical studies of various material parameters such as backings, matching layers, width/thickness ratios, and bonding techniques cost-prohibitive. Additionally, wire guide arrays have a large variance in element performance, partially due to acoustic ringing in the relatively large wires located directly beneath the elements. Fabrication difficulties prohibit the use of shielded coaxial cable in wire guide transducers, leading to high electrical cross-coupling due to the close proximity of unshielded wires. Even with unshielded wire, difficulties in hand routing 150 µm diameter wires currently limits this technique to a minimum pitch of 300 µm, corresponding to a maximum frequency of approximately 3.5 MHz.

Greenstein et al. [10] have recently described a wire guide interconnection scheme utilizing 50 µm etched Be/Cu conductors embedded in an epoxy backing which offers further increases in connection density. Electrical connection of the wire guide to a pad grid array is provided by an anisotropic elastomeric material, which may ultimately limit connection density.
In 1993 we reported a multilayer ceramic (MLC) connector based on thick film hybrid circuit technology [11]. This device, similar in concept to a multilayer printed circuit board, routes signals from the base of the 2-D elements through several distribution layers to a connector which mates with the transducer handle. The MLC is a custom thick film hybrid circuit consisting of a stack of sintered alumina green tape with screen-printed traces and vias. Using an MLC, the transducer fabrication effort was reduced from 6 weeks to 3 days. Additionally, by using interleaved ground planes, electrical impedance and crosstalk were controlled. The primary disadvantage of the MLC was acoustic reverberation within the ceramic backing due to the nearly identical acoustic impedance of alumina and PZT (29 MRayls). The low acoustic attenuation of alumina provided little damping. In order to reduce the transmission of acoustic energy into the MLC, a conductive \( \lambda/4 \) mismatching layer was employed between the PZT and MLC. Unfortunately, the broadband nature of the transducer made the narrowband mismatching layer largely ineffective. Other disadvantages of the MLC included high tooling costs and long lead times. Several MLC prototypes were fabricated, including a 50 layer MLC from Kyocera of America and a 70 layer device manufactured by IBM. These devices were used to fabricate transducer arrays of up to 40 \( \times \) 40 = 1600 elements with 484 active elements operating at 2.0 MHz.

We recently developed an alternative to hand wired or MLC array interconnection which consists of a flexible polyimide interconnection circuit. This multilayer flex (MLF) circuit consists of one or more thin films of polyimide with electrical traces routing signals horizontally and plated-through vias routing signals vertically between layers. The MLF performs the same function as the MLC but is implemented as a thin interconnect layer between the PZT and the normal backing material. If sufficiently thin, the MLF circuit may be considered an acoustic membrane. Acoustic reverberations which plagued MLC transducers are eliminated because the acoustic impedance of polyimide (3.1 MRayls) is well matched to the backing and poorly matched to PZT. MLF circuits may be fabricated with smaller feature sizes than drilled wire guides or MLC circuits, allowing increased element density and high transducer center frequencies. MLF transducers have the advantage of reduced fabrication effort compared to wire guides and reduced manufacturing costs compared to MLC circuits, especially in prototype quantities.

Single sided flex circuits have been routinely used for edge connections to commercial 1-D transducer arrays. However, interconnection of 2-D arrays requires connections to the base of isolated elements, making simple edge connection impossible. The interconnection of 2-D array elements using a proprietary polyimide based electrical circuit was proposed in 1990 by Smith et al. [12]. Robinson and Mo [13] proposed a silicon based thin film interconnection scheme for 2-D arrays in 1992. In 1995 we briefly reported an alternate fabrication technique based on a 2 layer thin film flex circuit [14]. This report included a functional 41 \( \times \) 41 = 1681 element 2-D array transducer with 120 active elements, a 400 \( \mu \)m pitch and a center frequency of 2.5 MHz. A 512 element 1.5-D array has also been reported by Tournois et al. [15] which has a polyimide based interconnect scheme with a single layer of metal traces.

Our hypothesis is that custom MLF circuits may be used for the interconnection of high density 2-D arrays, including high frequency arrays which cannot be fabricated using conventional wire guides or MLC technology. The MLF circuits may be made acoustically thin or may be matched to the backing impedance, yielding performance which is equivalent or superior to wire guide transducers at drastically reduced fabrication effort. This technology is applicable for high frequency designs, and our current work is at 2.2 MHz to ease fabrication and allow direct comparisons to wire guide transducers.

We describe the design, analysis, and fabrication of 2-D arrays using MLF circuits for element interconnection. The one-dimensional KLM model is used to compare the predicted performance of MLF and wire guide 2-D arrays. Fabrication of a 2-D array using a 5 layer MLF circuit with 256 active elements operating at 2.2 MHz is described. Experimental data from the MLF transducer is compared to a conventional wire guide 2-D array of equivalent dimensions. B-scan images of tissue mimicking phantoms using the MLF and wire guide transducers on the Duke phased array ultrasound scanner are presented.

II. METHODS

The structure of a 2-D wire guide transducer and MLF transducer are compared in Fig. 1. Both transducers util-
lize a conductive λ/4 matching layer with a foil ground plane at the top of the array. In the wire guide transducer of Fig. 1(a), the PZT is electrically connected to the wire guide using a conductive epoxy. The wire diameter is typically greater than 1/2 the element width. In the MLF transducer of Fig. 1(b), the PZT is electrically connected to pads on the top surface of the MLF circuit using conductive epoxy. Electrical signals are routed vertically from the base of the elements down through the top polyimide layer of the MLF circuit. The signals are routed horizontally on internal trace layers to the pads of peripheral double sided edge connectors. This illustrative flex circuit is comprised of two internal trace layers and a single internal ground plane, although other combinations of trace layers and ground layers are possible. Beneath the flex circuit is the backing material, which may be composed of a low acoustic impedance material to improve sensitivity, or a higher impedance lossy material to improve bandwidth.

The MLF circuits used in this study were fabricated by commercial flex circuit manufacturer. Multilayer circuits were fabricated by laminating together single layer circuits using mechanical alignment. The registration tolerance of blind mechanical alignment placed a lower limit on via pad size (around 150 μm) and ultimately limited the pitch of the connections, regardless of the number of trace layers. The state-of-the-art for laminated MLF circuits is a film thickness of at least 25 μm, via diameter of at least 50 μm and trace width of at least 50 μm.

The MLF and wire guide transducers were modeled using a commercial version of the one-dimensional KLM model (Sonic Concepts, Woodinville, WA). Although the accuracy of the model was limited due to the complex 3-D transducer structure, the 1-D model was useful for first order predictions of transducer performance. More accurate modeling of the wire guide and MLF structure could be provided by 2-D and 3-D finite element analysis [16], [17].

The acoustic stacks of the wire guide and MLF transducers are compared in Table I. The wire guide transducer model included silver foil ground plane, silver epoxy matching layer, bar mode PZT, and a light epoxy backing. The MLF transducer model was identical except the MLF circuit structure was inserted between the PZT and backing. The wire guide was modeled as an epoxy backing layer, ignoring the metal wires. This provided a best case prediction of the wire guide transducer performance, which served as the control in our comparisons.

A cross-sectional diagram of the MLF circuit used in this study is shown in Fig. 2. The MLF circuit was modeled as alternating polyimide and metal backing layers. In order to provide a worst case prediction of the MLF, we assumed metal was present on both trace layers. Because the trace width (50 μm) was much smaller than element width (350 μm), and traces were not always routed beneath elements, this model was only approximate. The via structures (50 μm diameter) within the polyimide layer were ignored and were another source of error in the 1-D model.

Electrical properties of the MLF circuits such as characteristic impedance, capacitance, and cross-coupling are useful to predict MLF transducer performance. Structurally the MLF circuits are similar to microstrip circuits. However, in the MLF, the metal traces are completely encapsulated in dielectric rather than lying on top of the dielectric. Also, typical microstrip trace thickness is small relative to the dielectric thickness and may be ignored. However, in the MLF connector we have minimized the polyimide thickness in order to reduce acoustic ringing in the connector, leading to a large relative trace thickness.

As with coaxial cable, the characteristic trace impedance (Z₀) for the MLF is dependent on its physical dimensions and dielectric properties. For an MLF with trace thickness t and width w, separated from a ground plane by a dielectric of thickness h and relative dielectric constant εₑ, Z₀ is given by [18]:

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{\text{eff}}}} \left(1.67 \frac{w}{h} + 2.36\right) \quad (\Omega) \quad (1)$$

for $w/h \geq 1/2\pi$. The effective trace width to dielectric thickness ratio is:

$$\frac{w_\text{e}}{h} = \frac{w}{h} + \frac{1.25t}{\pi h} \left(1 + \ln \frac{2h}{t}\right) \quad (2)$$

and the effective relative dielectric constant is:

$$\varepsilon_{\text{eff}} = \varepsilon_r - \frac{(\varepsilon_r - 1)t/h}{4.6\sqrt{w/h}}. \quad (3)$$

From (1) we see that the trace width or dielectric thickness may be adjusted to obtain a desired characteristic impedance.

The close proximity of parallel traces within the MLF makes electrical cross-coupling a concern. We have, therefore, included a ground plane in the design to reduce mutual capacitance between traces. The mutual capacitance per length, $C_m/l$, between two parallel traces encapsulated in a dielectric is given by:

$$\frac{C_m}{l} = \frac{\varepsilon_{\text{eff}} \varepsilon_0}{\pi} K_c K_L \left(\frac{w}{x}\right)^2 \quad (\text{F/m}) \quad (4)$$

where x is the separation distance between traces, $\varepsilon_0$ is the permittivity of free space, $K_c$ is a factor which takes into account electric field fringing given by:

$$K_c = \frac{120\pi}{Z_0 \sqrt{\varepsilon_{\text{eff}}}} \left(\frac{w_\text{e}}{h}\right)^{-1}. \quad (5)$$
and $K_L$ is an inductive fringing factor which is equal to $K_C$ in this configuration. Mutual capacitance is the primary mechanism of electrical cross-coupling between traces, and depends on the source and load impedances. Cross-coupling due to mutual inductance is relatively minor when the load impedance is much greater than the trace impedance [19].

Although the ground plane is beneficial for reduction of electrical cross-coupling, it creates a shunt capacitance, $C_s$, from trace to ground given by [19]:

$$C_s = \epsilon_{eff} \epsilon_0 K_c \left( \frac{w_c}{h} \right).$$

In the Duke scanner, high input impedance preamplifiers are located in the transducer handle. Therefore, on receive the low capacitance 2-D element are mainly loaded by the shunt capacitance of the MLF circuit. Because preamplifier noise is dominant, capacitive loading reduces system SNR. The lumped capacitance of the MLF circuit was similar in magnitude to the clamped capacitance of the 2-D array elements ($\approx 5 \, \text{pF}$), resulting in a signal loss of approximately 6 dB.

A sparse periodic 2-D array was used for the prototype MLF connectors. The array had 192 transmit elements and 64 receive elements out of a total of 1320 elements in a 16.4 mm aperture. The array was designed to operate at 2.2 MHz and had a pitch of 400 $\mu$m with 50 $\mu$m kerf. The transmit element spacing (0.59 $\lambda$) provided a wide transmit beam necessary for receive mode parallel processing, and a larger receive spacing (2.9 $\lambda$) was used to improve lateral resolution. The pulse-echo grating lobes were reduced by minimizing the overlap of individual transmit and receive grating lobes [7], [20].

The MLF circuits were fabricated by an external manufacturer (Litchfield Precision Components, Litchfield, MN). Using 50 $\mu$m wide traces and 50 $\mu$m minimum spaces, two trace layers were required for 256 element connections. Note that the upper polyimide layer (Fig. 2) has been made thicker than buried layers to facilitate physical and electrical isolation of the elements by dicing partially into the upper polyimide layer without disturbing underlying structures. The adhesive material used to bond the layers was not included in the table and is assumed to be acoustically thin. The total connector thickness was 206 $\mu$m, which corresponds to $\lambda_p/5$, where $\lambda_p$ is the acoustic wavelength in polyimide at 2.2 MHz.

After the MLF connectors were procured, the following fabrication procedure was followed. First a conductive silver epoxy (Chomerics 584, Woburn, MA) matching layer was cast and slipped into an automated lapper (Hoffman PR-2, Carlisle, PA) to 170 $\mu$m thickness. The matching layer was then bonded to a 610 $\mu$m thick PZT chip (3203HD Motorola, Albuquerque, NM) with silver epoxy. The PZT/matching layer assembly was bonded to the MLF connector with silver epoxy and diced (Kulicke & Soffia, model 780) into individual elements. The kerf depth was limited to 25 $\mu$m to avoid cutting buried traces. After dicing, a silver foil (12.5 $\mu$m thick) ground plane was attached to the top surface of the array with conductive epoxy. Finally, a light epoxy backing (Araldite 502/955) was cast into place to complete the transducer fabrication.

III. Results

A. Circuit Characteristics

The prototype MLF circuit designed and fabricated for this study is shown in Fig. 3(a). In the center of the circuit is the sparse periodic pattern of 256 pads to provide connections to the base of the active elements. Traces are routed internally to pads on the four peripheral insets which will be folded 90 degrees and inserted into flex circuit edge connectors. Each double sided edge connector (Precision Interconnect PAC, Portland, OR) provides 2 x 36 = 72 connections at a 25 mil pitch. A completed MLF transducer is shown in Fig. 3(b). The silver foil ground plane is visible on the top surface covering the octagonal diced PZT chip.

The characteristic impedance of an MLF trace was computed using (1). The characteristic impedance was calculated to be 32 $\Omega$, given a trace width of 50 $\mu$m, trace thickness of 18 $\mu$m, dielectric thickness of 25 $\mu$m, and relative dielectric constant of 3.4. Calculation of mutual capacitance was complicated by the nonuniform conductor spacing within the MLF circuit. The calculation of capacitance...
in Fig. 4(a). The primary resonance is seen at 2.5 MHz, with an additional resonance at 1.6 MHz due to the PZT-matching layer combination. Fig. 4(b) shows the simulated impedance plot of an MLF transducer element with a primary resonance at 2.7 MHz and a resonance at 1.5 MHz due to the combined PZT and matching layer.

Fig. 4(c) shows the simulated impulse response and spectrum of the wire guide element, which had a 62% fractional bandwidth, −6 dB pulse length of 0.58 μsec, and −20 dB pulse length of 2.0 μsec. The MLF element (Fig. 4(d)) was similar, with a simulated fractional bandwidth of 71%, −6 dB pulse length of 0.52 μsec, and −20 dB pulse length of 2.2 μsec. These results indicate that at this frequency the acoustic impact of the MLF was minimal. Further analysis has shown that the epoxy bond at the base of the PZT elements has a significant impact on transducer performance, effectively masking subtle differences between the wire guide and MLF transducer elements.

The acoustic impact of the metal traces was investigated by repeating the simulation after replacing the MLF stack with a single polyimide layer of equivalent total thickness. The results of this simulation indicated that the slight difference in predicted performance between the wire guide and MLF transducers was due to the metal layers.

The simulated peak pulse-echo amplitude of the MLF transducer element was 6 dB lower than the wire guide element due to the shunt capacitance of the MLF circuit. The 5 pF trace capacitance and 3 pF capacitance of the coaxial leads were included as a lumped shunt capacitance at the electrical port of the model. This capacitance loaded down the receive signal seen at the high impedance preamplifiers located in the transducer handle. In a system with preamps in the scanner, there would be little loss in sensitivity due to the MLF since its shunt capacitance would not be significant when compared to the 100 pF/m cable capacitance.

2. Experimental Results: Electrical impedance of the fabricated wire guide and MLF transducer elements was measured in air using an HP4194A impedance analyzer. The impedance plot of a typical wire guide transducer element, shown in Fig. 5(a), has a series resonant frequency of 2.2 MHz and a resonance at 1.5 MHz due to the combined PZT and matching layer. The MLF transducer element impedance plot of Fig. 5(b) has resonances at 2.2 MHz and 1.4 MHz. Third harmonics are clearly visible. No spurious resonances accountable to the MLF circuit are visible, which is consistent with KLM simulations.

Impulse response measurements were made in a water tank by shock exciting an element with a 250 V impulse (Metrotek MP 215 pulser). The echo signal from a polished aluminum reflector was received on an adjacent element. Fig. 6 compares the measured impulse response of a wire guide transducer element to an MLF element. The wire guide transducer element impulse response shown in Fig. 6(a) has a −6 dB pulse length of 1.2 μsec and a −20 dB pulse length of 3.8 μsec. The MLF transducer impulse response shown in Fig 6(b) is similar, with a −6 dB pulse length of 1.0 μsec and a −20 dB pulse length of 2.7 μsec.

B. Transducer Characteristics

1. Modeling Results: The KLM model was used to predict performance of the wire guide and MLF transducer elements using the acoustic properties and dimensions listed in Table 1. Modeling results are shown in Fig. 4. The simulated wire guide transducer impedance in air is shown between typical adjacent MLF traces was accomplished by first calculating the mutual capacitance of individual trace segments using (4) and adding the results to yield the total lumped mutual capacitance of 0.02 pF. Theoretical MLF trace to ground capacitance was calculated using (7) to be 0.18 pF/mm. Given an average trace length of 27 mm, the lumped shunt capacitance was predicted to be 4.9 pF. The MLF shunt capacitance of 15 typical traces was measured with an HP 4194A impedance analyzer to be 4.98±0.18 pF.
Fig. 4. The KLM modeling results: Impedance of (a) wire guide transducer and (b) MLF transducer. Impulse response and spectra of (c) wire guide transducer and (d) MLF transducer.

Fig. 5. Measured impedance plot for (a) wire guide transducer and (b) MLF transducer.
Measured pulses exhibit extended ringing with amplitude near -20 dB due to cross-coupling, which was not taken into account by the KLM model. Variations in bond thicknesses and limitations of the 1-D model account for increases in the measured pulse lengths when compared to model predictions.

The spectra of the pulse-echo impulse response of wire guide and MLF transducer elements were measured with an HP 3588A spectrum analyzer and are compared in Fig. 6. Both elements had a center frequency of approximately 2.2 MHz. The wire guide transducer spectrum shown in Fig. 6(c) had a peak amplitude at 2.0 MHz and a -6 dB fractional bandwidth of 52%. The MLF transducer spectrum shown in Fig. 6(d) had a peak amplitude at 2.2 MHz and -6 dB fractional bandwidth of 64%.

The pulse-echo signal from a 5 cm deep reflector was measured for 24 randomly selected element pairs of each transducer. The wire guide transducer signal was 16.9 ± 2.6 mV. The MLF transducer signal was 9.4 ± 0.51 mV. The lower sensitivity (-5 dB) of the MLF transducer was
due to the capacitive loading of the circuit traces and coaxial lead wires and is consistent with KLM modeling. The high variation of element sensitivity in the wire guide transducer is most likely due to variations in the location of the 250 μm diameter wires beneath each element.

Interelement cross-coupling was measured by exciting an element with a broadband impulse (250 V, Metrotak MP 215 pulser) and measuring the coupled signal on an adjacent element. When possible, elements adjacent to the source element were electrically loaded to accurately represent the scanner configuration. However, unconnected elements of the sparse array could not be electrically loaded. Cross-coupling measurements were performed in a water tank to acoustically load the elements. This time-domain measurement was dominated by the electrical cross-coupled signal which appeared simultaneously on both the source and measured element and had similar spectral content. In both the wire guide and MLF transducers, electrical cross-coupling was greatest between adjacent circuits in the pin grid array connector (which is the interface to the transducer handle) rather than at the transducer face. The cross-coupled signal in the wire guide transducer was 14.9 ± 2.4 volts yielding an average cross-coupling of −24.5 dB. Cross-coupling in the MLF transducer was 6.9 ± 1.2 volts for an average cross-coupling of −31.2 dB.

An alternate frequency domain cross-coupling measurement was made with the MLF transducer using an HP 3588A spectrum analyzer. This measurement was used to identify sources of electrical and acoustic cross-coupling from 100 KHz to 10 MHz. The spectrum analyzersource output (50 Ω) was connected to one transducer element. The coupled signal on an adjacent channel was measured using a FET probe (Tektronix P6201) and the ratio of input signal to coupled output signal was computed. The high impedance FET probe (1.5 pF, 10 MΩ) was used to represent the high impedance preamps located in the transducer handle of the Duke scanner. Fig. 7 is a plot of electrical and acoustic cross-coupling for two pairs of elements. Electrical cross-coupling was measured by selecting two circuits which were adjacent throughout most of the connector but were terminated in spatially separated elements, minimizing acoustic cross-coupling. The results indicate peak electrical cross-coupling of −37 dB at 2.4 MHz. Acoustic cross-coupling was measured by selecting two circuits which were spatially well separated but terminated in adjacent elements. The peak acoustic cross-coupling was −28 dB at 1.7 MHz. Although this swept frequency measurement indicates the frequency of cross-coupling sources in the MLF, it does not indicate phase, making integration of the signal across the system bandwidth impossible.

The −6 dB element angular response was measured by shock exciting an element and measuring the emitted signal versus angle at a range of 5 cm using a needle hydrophone (Dapco Industries, Ridgefield CT). The one-way response was squared to yield the pulse-echo angular response, assuming transmit and receive reciprocity. The −6 dB beamwidth was measured to be 11.2° ± 4.1° for the wire guide elements and 43.5° ± 4.4° for the MLF elements. The theoretical −6 dB beamwidth of a 2.2 MHz, 350 μm wide element surrounded by a soft baffle is 70° [21]. These results indicate that both element types suffer from significant cross-coupling, although the wire guide cross-coupling is more severe. Because angular response was measured when the transducer was disconnected from the scanner, element connections floated electrically and may have had greater electrical pickup (and crosstalk) than when attached to the scanner. Fig. 8 compares the measured angular response of a typical wire guide element and MLF element to the theoretical angular response [21]. The narrow beamwidth and peaked sidelobes of the wire guide element are indicative of high cross-coupling [22].

The wire guide and MLF transducers were attached to the Duke phased array scanner and used to make B-scan images. A sector angle of 70° was selected, with a transmit focus at 70 mm and dynamic receive focusing. Fig. 9 compares images of a 2.4 cm spherical cyst located 6 cm deep in a tissue mimicking phantom (Madison, University of Wisconsin). The image made with the wire guide transducer [Fig. 9(a)] had similar image quality as the MLF transducer shown in Fig. 9(b). Both images were made with identical system settings with the exception of system
gain, which had to be increased for the MLF transducer due to its reduced sensitivity and penetration depth.

IV. Discussion

We have successfully applied multilayer flex circuit technology to the interconnection of 2-D transducer arrays. Two-dimensional array transducers using conventional wire guide and MLF interconnection were fabricated and characterized. Fabrication time was reduced from 6 weeks to 3 days using the MLF circuit, making empirical studies of 2-D array transducer parameters possible. Both transducers had a center frequency near 2.2 MHz and had similar impedance, pulse shape, and bandwidth. The metal traces of the MLF did not cause significant degradation in element response because the trace thickness was less than 1/100. Because the polyimide dielectric was poorly matched to the PZT impedance and well matched to the backing, no reverberation problem was observed in the MLF transducer. Significant improvement in element angular response was achieved in the MLF by employing a ground plane to reduce electrical cross-coupling. Similar performance could not be achieved using wire guides since the use of coax is not practical. Reduced electrical cross-coupling was achieved at a cost of increased trace-to-ground shunt capacitance, which reduced penetration depth in images made using the Duke scanner. However, if used in a system with preamps located in the scanner, the MLF shunt capacitance would be minor compared to the cable capacitance. Element variability was lower in the MLF transducer, which is important in highly tuned systems and for two-dimensional phase correction.

A primary concern of the performance of MLF transducers is acoustic coupling between adjacent elements in the polyimide material. In conventional transducer fabrication, the saw kerf extends into the backing material to reduce lateral coupling between elements. To avoid disturbing underlying traces, the kerf depth in MLF transducers is limited to 25 μm by the thickness of the top polyimide layer. A possible solution to this problem is to include a lossy conductive layer between the base of the elements and the top of the MLF. Also, the acoustic attenuation of this layer could further reduce reverberations within the connector and backing.

A difficulty inherent with any high density 2-D array interconnection is electrical cross-coupling due to the close proximity of the circuits. In the MLF, the ground plane is the most important solution to this problem, reducing mutual capacitance by an order of magnitude. Increasing the trace separation is also beneficial but may require additional trace layers. However, using lamination technology, additional layers may not be practical beyond five metal layers. Ideally, a ground plane should be located between the base of the PZT elements and the top internal trace layer to prevent unwanted elements from being activated by capacitive coupling to signals on traces which are routed beneath them. This top ground plane could be connected to all unused elements of a sparse 2-D array, electrically clamping them. This technique, which is not practical with wire guide transducers, could further reduce cross-coupling and improve element angular response.

The footprint of the MLF transducer shown in Fig. 3(b) extends beyond the acoustic aperture due to the four peripheral interconnects. For practical MLF transducers suitable for medical imaging, this footprint must be reduced while increasing the number of active elements. Location of vertical silicon circuit interconnects behind the transducer elements has been proposed by Robinson and Mo [13]. We recently developed an interconnect method in which perpendicular flex circuits are connected to the back side of the MLF behind the 2-D elements. This configuration, shown in Fig. 10, allows increased density of connections without increasing the transducer footprint. We are currently investigating fabrication methods which will provide electrical connection of the vertical circuits to the MLF.
with minimal acoustic impact on element response.

We have briefly reported a 3.5 MHz, 350 µm pitch, 72 x 72 = 5180 element sparse array with 428 active elements fabricated using an MLF circuit with the vertical interconnect design [23]. Six double sided flex circuits were required, each providing 2 x 36 = 72 connections at 25 mil pitch, yielding a total of 432 connections in one square inch. The MLF circuit used in this transducer represents the state-of-the-art for laminated multilayer flex circuits made using mechanical alignment of layers. Further increases in transducer frequency or element density would require additional trace layers. Above 5 MHz the via pad size approaches the element pitch, making interconnection impossible, regardless of the number of layers.

MLF circuits with smaller feature sizes may be manufactured using thin film processes to allow increased density and transducer frequency. These methods rely on optical techniques to align adjacent layers to within one micron, thus drastically reducing via pad diameter. Dielectric thickness may be decreased from 25 µm to under 10 µm by using a spin deposition technique where a thin layer of uncured liquid polyimide is deposited on the circuit substrate. Vias are chemically etched and the remaining film is cured at high temperature. Via diameter may be reduced from 50 µm to under 20 µm with via pad size reduced from 150 µm to under 30 µm. Thin film circuits provide a much thinner connector without adhesive layers and should yield a transducer with more uniform, predictable, element response. Using thin film processes, we have successfully designed and fabricated a 256 element MLF circuit which requires a single trace layer to provide the same interconnects as the two layer laminated MLF circuit used in this study. The extra trace layer was eliminated by reducing the trace width to 20 µm and via pad size to 70 µm.

Electrical characteristics of the MLF such as impedance and capacitance are not affected by reducing feature sizes as long as the proportions of trace width to dielectric thickness are maintained. As trace sizes are reduced, electrical resistance of the trace becomes significant and could result in signal loss and resistive heating in the circuit. To avoid this problem we have increased the thickness of the traces by electroplating, but ultimately trace resistance may limit miniaturization of the interconnect.

To assess the performance of an MLF transducer at higher frequencies, the KLM model was used to compare the impulse response from a 7.5 MHz array with light epoxy backing to an identical element with a thin film MLF circuit. Because previous simulations indicated that the bond layer between the PZT and connector significantly degrades performance, an improved one micron thick bond was assumed in order to prevent the effects of bond thickness from dominating the simulation results. The simulated response of the element without the MLF, shown in Fig. 11(a), has a –6 dB bandwidth of 48%, a –6 dB pulse length of 0.22 µsec, and a –20 dB pulse length of 0.53 µsec. Fig. 11(b) shows the simulated impulse response for the element with the MLF structure included. The result is nearly identical, indicating that the acoustic impact of MLF interconnections for high frequency 2-D arrays should be minor. We believe that these results, in addition to our experimental results, show that multilayer polyimide circuit technology is a practical solution to the future challenge of high density 2-D array interconnection.

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**REFERENCES**


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