30 MHz Medical Imaging Arrays Incorporating 2-2 Composites

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Abstract – Methods for fabricating and modeling high frequency 2-2 composites and arrays are presented. The composites are suitable for arrays and small aperture single element devices. Coupling coefficients above 0.65 and lateral mode frequencies near 60 MHz have been achieved. Two prototype 4 element 30 MHz linear arrays were designed and built using this composite. Backing and matching layers were fabricated and characterized while coaxial cable was used to electrically tune each element and broaden bandwidth. The measured properties of passive and active components were used to analyze the design in a time-domain finite element analysis program. Agreement between experiment and theory was excellent.

1. INTRODUCTION

Very high frequency ultrasonic imaging is an exciting frontier in ultrasound. A rich variety of applications in dermatology and opthalmology await the development of imaging systems with less than 0.5mm resolution. In order to achieve this level of performance, novel fabrication techniques are needed in order to build arrays operating above 20 MHz.

Previous array achievements in this frequency range include a pair of 20 MHz PZT arrays [1][2], a 100 MHz array incorporating a sapphire lens and thin film ZnO [3], and a polymer array with built-in transmit and receive circuitry [4]. In addition, O'Donnel et al, in cooperation with Endosonics Corporation, describes the operation of a 20 MHz phased array imaging system for catheter use [5][6].

Linear arrays, which are typically not used with beam-steering, can tolerate a much larger element pitch than phased arrays. It is therefore practical to focus first on the development of linear arrays with 1λ to 2λ pitch. Although integrating the array with the electronics offers advantages, a more conventional and flexible approach of coupling the array elements to a 50 ohm imaging system has been adopted. Broad bandwidth (minimum of 40%) is desired, both to suppress grating lobes and improve the axial resolution. Crosstalk levels of near –30dB are considered acceptable for a linear array not incorporating Doppler. Finally, mild elevational focusing is desired for improved resolution in the elevation direction.

2. COMPOSITE

PZT "strip" vibrators (length >> width or height) require a width to height ratio of less than approximately 0.6 for proper pulsed performance. For 30 MHz operation each PZT strip must therefore measure a mere 30μm wide by 50μm tall. Compounding this size difficulty is the requirement that the spacing between each strip be less than 10μm in order to push spurious lateral resonances above the passband and maximize capacitance. Conventional dicing and filling technology presently cannot be used to manufacture this structure.

An alternative fabrication technique is to stack ceramic and polymer layers to form a block of composite material, then slice sections from this block. Variants of this technique have been proposed previously, including once for high frequency arrays [7]. The difficulty is in controlling the ceramic and polymer dimensions. One way of addressing this difficulty is described next.

Fine grain PZT-5H equivalent material (TRS 600, TRS Ceramics, State College, PA) was lapped to a thickness of 33μm using a precision lapping process. Numerous plates of this material were stacked and bonded together using Epo-Tek 301-2

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epoxy (Epoxy Technology, Billerica, MA). The plate to plate spacing was controlled by incorporating polystyrene spheres into the bonding epoxy. These spheres (#PS06N, Bangs Laboratories, Fishers, IN) possessed a nominal diameter of 6.20μm, with a standard deviation of only .09μm. The spheres were incorporated into the epoxy at a volume fraction of 5%. Plates of 5mmx5mm ceramic and a consistent amount of loaded epoxy were stacked in an alternating fashion. The stack was constrained from lateral motion and light, uniform pressure was applied during the room temperature overnight cure. Thin sections of this stack were diced from the block, lapped to a thickness of 62μm, electroded with 4000A° of Au over a thin Cr layer, and poled at 2000V/mm and 50°C.

Analysis of the performance was quite encouraging and showed that these materials can be applied to both single element and array designs. Table I lists the results. Note the small standard deviation in kerf, indicating this technique can provide a controlled polymer width. The observed value for the lateral mode frequency corresponds closely to the d_{31} vibration of the ceramic plate, a well known result for volume fractions exceeding 75% [8].

A theoretical investigation of the composite performance has been performed using a dynamic model based on guided wave propagation [8]. Agreement with experimental results was exceptional, as shown in Table II below. Using this model a dispersion curve that predicts resonant frequencies over a range of thicknessess was obtained.

Table I – Measured Composite Properties

Kerf width	7.7μm
Standard deviation of kerf	0.3μm
Ceramic width	33.5μm
Standard deviation of ceramic	0.5μm
Dielectric constant, $\epsilon_{33}{}^{S}/\epsilon_0$	1100
Thickness velocity at F_p	4050 m/s
1^{st} lateral mode frequency	58.8 MHz
Coupling coefficient k_t	0.67

Fp is the parallel resonance frequency

Table II – Predicted Composite Properties

Thickness velocity at F_p	4108 m/s
1^{st} lateral mode frequency	58.5 MHz
Coupling coefficient k_t	.71

Although developed for high frequency arrays, this composite fabrication technique is easily adapted to single element transducers. A wide diversity of ceramics, polymers, and particles can be used to achieve desired properties, while nonuniform structures are easily produced.

3. PASSIVE MATERIALS

Although the 2-2 composite is the heart of each element, backing and matching materials are needed to increase device sensitivity and bandwidth. A brief list of a few of the tested materials and their properties is displayed in Table III.

Materials 1 thru 4 were used as matching layers while material 5 was employed as the backing. These materials were prepared in an effort to approximately match the impedances determined from one dimensional modeling. For example, materials 2 and 3 perform well as double matching layers. Although finite element modeling appears better suited to this materials selection task, the FEM model requires actual materials values for longitudinal and shear velocity and attenuation. Optimizing four variables is a daunting task. Until further materials data becomes available it is more manageable to select the longitudinal impedance using one dimensional modeling.

Lens requirements include a longitudinal velocity significantly different from tissue and a longitudinal impedance close to tissue. Material 7, TPX (polymethylpentene, Mitsui Petrochemcials, Ltd.), meets these requirements. Since the longitudinal velocity is greater than tissue, a concave lens design will be required. This is preferred over the typical lossy convex silicone lens, since attenuation in a concave design may be used to favorably apodize the beam [9]. Another option for lens design is material 1, which possesses extremely low attenuation but a higher longitudinal acoustic impedance. Further work in lens selection and fabrication is continuing.

Table III – Passive Materials Properties Measured at 30 MHz

#	Material	Density (g/cm^3)	$Velocity_{long}$ (m/s)	$Velocity_{shear}$ (m/s)	$Atten._{long}$ (dB/mm)	$Atten._{Shear}$ (dB/mm)
1	Epo-Tek 301	1.15	2740	1270	13	50
2	Polystyrene, cross-linked	1.06	2340	-	1	-
3	Epo-Tek 301, 61% Al_2O_3	2.04	2920	-	13	-
4	Epo-Tek 353ND	1.22	2770	1230	6	32
5	E-Solder 3022, conductive epoxy	2.59	2110	1020	40	100
6	Epo-Tek 301-2 w/ spheres (composite filler)	1.14	2660	1260	9	32
7	TPX	0.82	2170	-	6	-

4. ELECTRICAL MATCHING

Given the small size of the elements the electrical impedance is several hundred ohms. In order to match these devices to a 50 ohm system a transformer is required. For this array excellent results were achieved using the coaxial cable connecting each element to the system.

Using transmission line theory, 85 ohm micro-coax from Precision Interconnect (Portland, OR) was selected to transform the impedance, tune out reactive components, increase bandwidth, and "fine tune" the center frequency. This technique is, of course, limited to frequency ranges where approximately a quarter wavelength of coax is a convenient length. In this case an almost ideal length of 2.09 meters was required. In addition, coax with the proper electrical impedance must be available. As will be shown later, when these two criteria are met a single quarter wave matched transducer achieved 65% bandwidth, equalling that typically obtained with dual matching layers. This is a significant improvement of the design and is a benefit of working at high frequencies. No inductor was used since the phase angle within the passband reached 0°, while 2-way losses in the coax were less than 2dB.

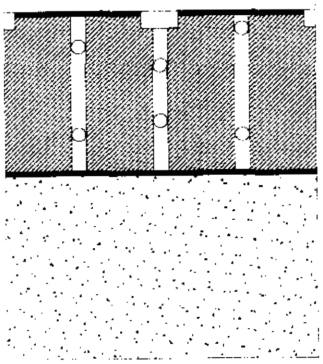
5. MODELING AND DESIGN

Both one dimensional equivalent circuits and multi dimensional finite element models were used to analyze the design of the finished array. The Redwood equivalent circuit in PSPICE was used to select matching and backing materials and provide general design guidelines. For a more accurate representatation of the array, the time domain finite element code PZFLEX (Weidleinger Associates, Los Altos, CA) was used.

Figure 1 shows a cross section of the array design. Two ceramic strips are shown per element and the elements are isolated on the face using a dicing saw and a 12μm wide blade. Although other ways to isolate the elements have been explored, dicing was found to be most reliable for these prototypes. The matching layer (Epo-Tek 353ND) was lapped to a thickness of 22μm and bonded to the face. The conductive backing provided the ground plane. Neither of these designs used elevational focusing or RF shielding, although the finished arrays will incorporate both. Connections to the coax from each element were made through wraparound electrodes on the sides of an intermediate array housing. The housing was made of a machinable ceramic with a low dielectric constant for minimized capacitive coupling to the conductive backing.

Several iterations of the desired design were investigated. The simplest design incorporated single front face matching and a pitch of 1.3λ. The finite element model predicted 45% bandwidth and a center frequency of 26.6 MHz. With double front face matching 61% bandwidth and a 29 MHz center frequency were predicted.

Fig. 1 – Array Structure



From the top, the matching layer is shown above the ceramic elements (cross-hatched), with the electrodes depicted as bold lines. The separations between the top electrodes are filled with bonding epoxy, while the separations between the elements are filled with the composite filler. The 6.2μm spheres are shown as circles. The conductive backing is at the bottom of the figure.

Increasing the pitch to near 2λ would improve lateral resolution and ease the interconnect requirements; however grating lobes could represent a problem. These grating lobes were investigated over the passband using a simple acoustic model. From this model, the ratio of the pulse-echo amplitude of the grating lobe to the main lobe was found to be a maximum of –19dB for excitation at discrete frequencies. If a pulsed response is considered, the 1-way amplitude is reduced by the ratio of the number of cycles in the pulse to the number of active channels [10], or at least -12dB for the two way amplitude. Grating lobes should therefore be at a manageable level of less than –30dB from the main lobe.

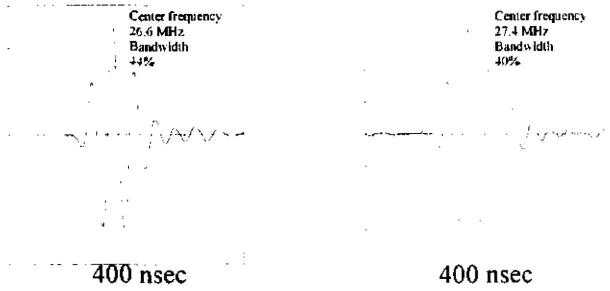
PZFLEX was found to be a powerful tool not only for predicting array performance but also for troubleshooting problems and determining design constraints. Figure 2 illustrates the excellent agreement between the experimental results and the PZFLEX model. Instead of requiring several iterations to achieve the desired results we were able to perform PZFLEX experiments until a suitable design was achieved. Issues such as the required depth of the isolation cut (between the major elements of the array), the required velocity and attenuation in the kerf filler, and the impact of bond lines were determined using this software.

6. EXPERIMENTAL RESULTS

Several four-element test arrays were constructed and tested to verify the modeling results and to assist in selecting the final design. The agreement between model and experiment was excellent.

A single matching layer was used on a 1.3λ spaced array. An isolation cut 5μm deep and 17μm wide was used to separate the elements. A representative experimental pulse-echo impulse response is shown with the modeled response in Figure 2. The amplitudes of the responses were all within 15% of the average and the pulse shapes were all similar. Maximum crosstalk between adjacent elements was found to be a –25dB.

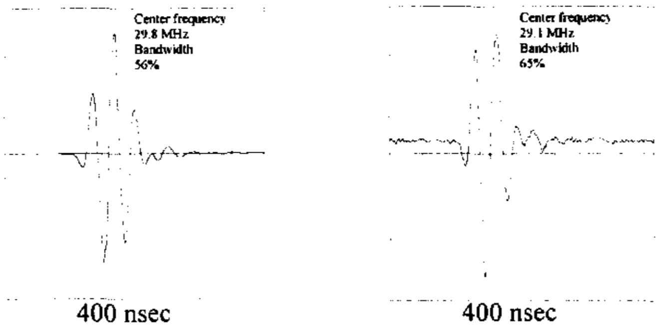
Fig. 2 – Normalized Impulse Response, 1.3λ Pitch Array



Model *Actual*

A second test array incorporating a single matching layer was also constructed. The element pitch was 2λ, with three ceramics per element. This resulted in a larger element and a lower electrical impedance when compared to the 1.3λ spaced array. This lower impedance was more effectively transformed to 50 ohms using the coax and broader bandwidth resulted. Experimentally, the bandwidth was 65% and the pulse length was less than 2 cycles. Figure 3 displays the modeled and experimental impulse responses for this array. Although there is some disparity between the actual and modeled results, the agreement is still good. Slight deviations in actual materials values, such as a shift of 1µm in the matching layer thickness, may account for the deviation.

Fig. 3 – Normalized Impulse Response, 2.0λ Pitch Array



Model *Actual*

7. FUTURE WORK AND ACKNOWLEDGEMENTS

A final design incorporating two matching layers and a deeper element isolation cut is being studied. Concurrently, a lens material is being adopted and a fabrication method tested and refined. Additionally, RF shielding will be added to the design. Once these tasks are finished a full 48 element array will be fabricated.

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