Triger, S. and Saillant, J-F. and Wallace, J. and Afroukh, F. and Wang, L. and Cochran, S. and Cumming, D.R.S. (2008) MOSAIC: A Scalable reconfigurable 2D array system for NDT. In, *Review of progress in Quantitative Nondestructive Evaluation, 22 - 27 July 2007* Review of progress in Quantitative Nondestructive Evaluation Vol 27B, pages pp. 1622-1629, Golden, Colorado, USA.

MOSAIC: A SCALABLE RECONFIGURABLE 2D ARRAY SYSTEM FOR NDT

S. Triger[1], J.F. Saillant[2], J. Wallace[1], F. Afroukh[2], L. Wang[1a], S. Cochran[2], and D.R.S Cumming[1]

[1] Microsystem Technology Group, Department of Electronic & Electrical Engineering, University of Glasgow, Glasgow, Scotland, UK, G12 8LT
[2] Microscale Sensors Group, School of Engineering, University of Paisley, Paisley, Scotland, UK, PA1 2BE
[1a] Formerly of the Microsystem Technology Group, University of Glasgow, now at Imperial College London, London, UK

ABSTRACT. This paper documents the development of a scalable 2D array system, or Mosaic that can be targeted at a wide range of NDT applications by way of a reconfigurable tile that can be tessellated to form arrays of any size and shape. Close coupling permits utilization of excitation voltages as low as +/-3.3V with insertion loss of 48dB on reflection from an aluminum back wall at 73mm achieved using 2D arrays without decoding.

Keywords: Integrated, Scalable, Array, System
PACS: 43.35.Yb, 43.35.Zc, 43.38.Fx, 43.38.Hz, 84.30.-r, 89.20.Kk

INTRODUCTION

Ultrasound imaging traditionally relies on collection of data in the time domain from a linear (1D) array to construct a 2D image of a plane that is perpendicular to the sample surface. Using generic building blocks of 2D elements to construct low cost ultrasonic arrays of any size and shape, a full 3D volume can be sampled from a single point allowing fast and accurate image collection with greater sample area or enhanced resolution obtainable by increasing the number of elements [1].

Due to dimensional constraints it is increasingly common for portable hand held array-based NDE systems to have electronics in close proximity to the transducer array. Impedance matching between transducers and electronics can be hard to achieve and retain in practical systems and cumulative mismatches over time can greatly impair the signal to noise ratio. This can potentially be resolved via the avoidance of cables.

This paper presents, as an alternative, the concept of a modular ultrasonic imaging system utilising generic building blocks of 2D array element configurations to construct low cost ultrasonic array systems of any size and shape, resulting in a fully scalable solution without requiring redesign. This system can be seen as a mosaic consisting of multiple modules, or ‘tiles’ which can be tessellated to form reconfigurable arrays of any size and shape for imaging of planar and non-planar surfaces allowing a full 3D volume can be sampled from a single point allowing fast and accurate image collection with greater sample area or enhanced resolution obtainable by increasing the number of tiles in the mosaic. Each integrates a high-frequency 16-element piezocomposite transducer array together with the electronics necessary for full transmit-receive capability on all 16 channels, thus resolving the scaling difficulties that exist due to corresponding increases in quantity and complexity of transmission and reception electronics [1, 2]. Unlike traditional ultrasonic systems, the drive electronics are situated adjacent to the sensor head to eliminate the use of long cables and hence minimise parasitic capacitances that degrade the strength of the received signal [1] which is of prime importance to enable low voltage excitation.

The ability to form ultrasound systems in this way from generic building blocks which are physically identical for manufacturing purposes yet functionally unique via programming to suit the application has the potential to transform NDE as it would permit the functionality of off the shelf hardware to be tailored to suit any given target application [3] in a field where equipment has traditionally been highly application-specific, a point increasingly considered in research in ultrasonics [4].

The next section provides more information on the basic concept and its potential applications. This is followed by more detailed technical information and, in the final part, results of early tests are presented.

THE TILE CONCEPT

Most ultrasonic imaging systems are designed for one particular application, typically defined in terms of parameters such as spatial resolution and range which are functions of the operating frequency, number of elements and aperture of the array. It is common practice to design the transducer array that suits the application and separately the electronics, then to combine them. Such bespoke solutions limit the range of applications, requiring a new system design when changes in any of the above parameters are called for. However, it can be argued that the quality of a system could be increased by having the electronics integrated with the transducer, yet still allowing for both to be modified to suit any given application.

The motivation behind this work was to miniaturize and integrate an ultrasonic system utilizing a 2D piezoelectric array transducer and its associated electronics. This ‘tile’ could permit the construction of larger array networks by tessellating multiple tiles side by side allowing control of the total aperture of the array and optimising performance for the application under consideration. Changes in the operational requirements of the system can be catered for by altering the functionality of the tiles in the system. This is the principal foundation of the MOSAIC concept presented in this paper, as shown in Figure 1 in which a single tile with electronics situated behind it can be cascaded with other tiles to form a larger array. Such a system is intended to provide the user with more flexibility in the range of applications without system redesign.

For a single tile to be sufficiently autonomous to operate alone, as much of the electronics must be housed on a tile as possible, with a minimum of functions shared between tiles. Such a design philosophy ensures the system is fully scalable, provided the bottleneck of taking data from tiles to the host PC can be overcome.

In previous research regarding the integration of piezoelectric transducers and electronics, only the front-end analog electronics was integrated [5]. This can cause a bottleneck for multiplexing to analogue to digital converter (ADC) inputs as the number of channels increases. Integration of CMUTs and electronics has resulted in the direct integration of MEMS and electronics by mounting an ultrasonic array onto the electronics substrate. The area occupied by the electronics is usually larger than that of the array, limiting the area under ultrasonic test to that of the array size and preventing array networks being formed by adjacent tiles due to the 'dead space' occupied by the electronics [6]. In order to achieve a mosaic network capable of 3D beam steering, it is necessary to situate the transducer elements on adjacent tiles at the same pitch as transducers in the same module [7]. The solution adopted was to situate the electronics behind the transducer.

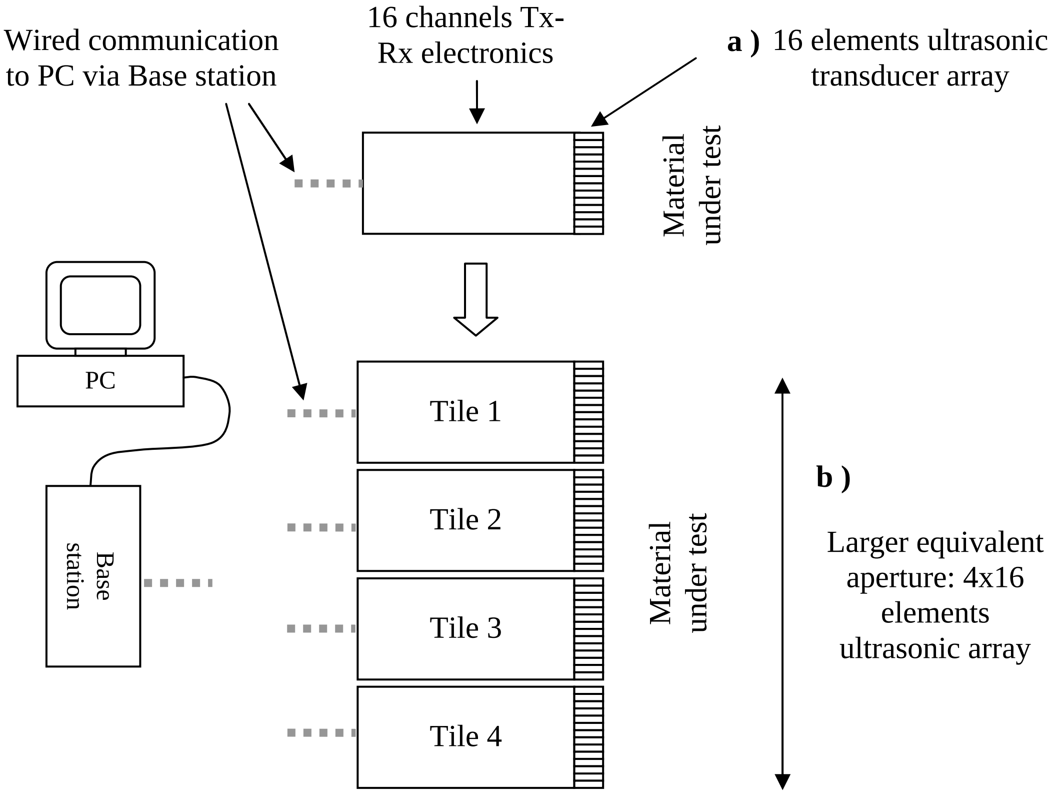

Figure 1. MOSAIC concept
a) A tile comprising a 16-element ultrasonic transducer array and integrated electronics for 16 Tx-Rx channels
b) A 64-element equivalent array aperture achieved by positioning four tiles side by side, and communicating data to a base station for processing.

Finally, it must be realised that this modular approach of electronics blocks and standardised yet flexible sub-arrays has significant potential for mass production and simplification of the fabrication processes, potentially simultaneously driving down cost while allowing end users to access optimum performance for their applications.

TILE DESIGN AND REALIZATION

The direct coupling of transducer and electronics provides the ability to lower excitation voltages however this inherently implies low signal to noise ratio (SNR). An attractive way to increase SNR is to use coded excitation waveforms [8]. Flexibility is the key to providing the user with the ability to excite any element of the transducer with any coded excitation sequence, such as Barker or Golay codes in order to maximise SNR. Such flexibility is achieved by incorporating the digital electronics within the tile in a field programmable gate array (FPGA) permitting two physically identical tiles can have very different functions.

The implementation of flexible electronics beam steering requires all elements in a tile to be capable of emitting and detecting signals at maximum timing resolution to give the necessary beam forming potential and focussing desirable for identifying defects in materials. The FPGA controls transmission of any coded sequence on any channel with a 10ns resolution and drives MOSFET drive circuits generating bipolar transducer excitation signals. Fusion of the transmission and reception electronics occurs at the transducer with the lack of cables between them permitting excitation voltages as low as +/-3.3V to be used to obtain adequate short-range reception signals. Each element has its own adjustable gain preamplifier after which the signals are multiplexed and time gain control is applied prior to digitization using a 12 bit ADC. A photograph of a tile is shown in Fig 2.

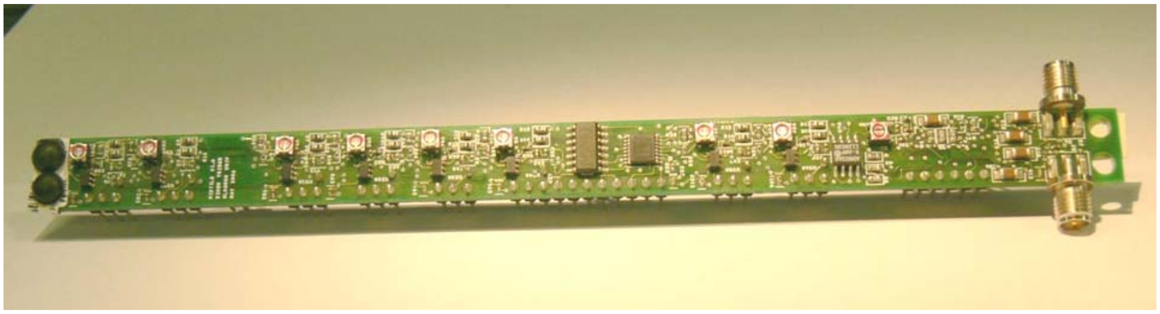

Figure 2. Photograph of the mid-tile electronics block (board 12mm wide)

The FPGA formats the digitized output for transmission to a host PC. The presence of an FPGA in each tile decentralizes a multi-tile system, important in order to make the system scalable. Front end real time digital post-processing functions can be implemented on the FPGA suiting functions like filtering and averaging as these can be pipelined effectively and, making best use of available resources without producing a data bottleneck.

The decentralised nature of the electronics permits a truly scalable solution as each tile in the MOSAIC system requires the same electronics, irrespective of the number of tiles in a system. This potentially improves upon current ultrasonic systems as it permits a generic tile to be used in a large multiplicity of applications, with reprogramming of the FPGA being the only adjustment required. Hence, it demonstrates that a cost effective, generic solution is possible in an area traditionally dominated by application specific solutions.

ULTRASONIC TRANSDUCERS

The tile as described uses a 2D array comprised of 4 1x4 array staves with a 1.21MHz centre frequency but the system can operate with either 1D or 2D transducers with a wide range of frequencies provided the aperture of the array is the same size as the electronics footprint. This is essential to allow the tiles to sit adjacent to one another in an application requiring multiple tiles. For the most efficient use of the electronics on a tile, the number of elements on a transducer array should equal the number of channels on the electronics. In the Mid-tile circuit there are 8 channels so 2 boards are placed adjacent to one another to accommodate the 16 channels required by the array. The electronics and the array still fit into the 16mm x 16mm footprint.

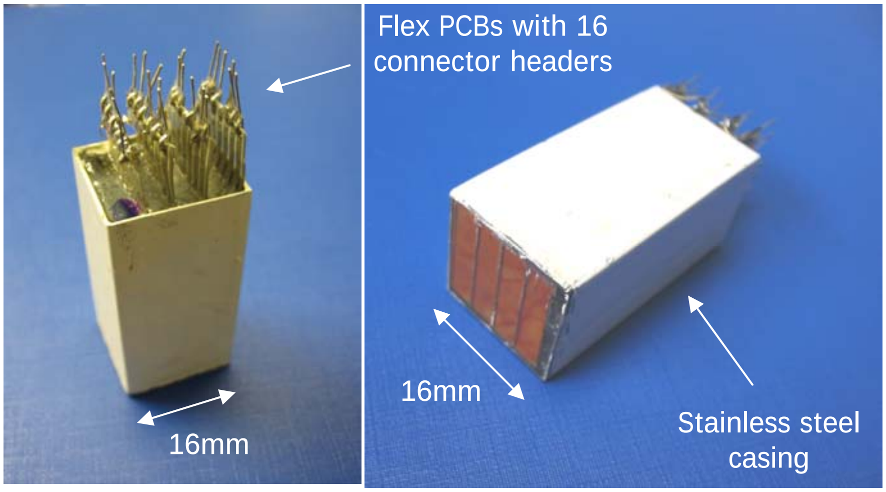

Figure 3. 4x4 element 2D array transducer

The transducer array was manufactured using 1-3 piezocomposite technology [9] due to its enhanced performance with respect to bulk piezoelectric ceramic technology due to greater electromechanical coupling coefficient and reduced lateral modes. When tested, the array had a 50% -6dB relative bandwidth and was manufactured in house using conventional manufacturing techniques [10].

RESULTS

To obtain preliminary results, the transducer array shown in Figure 3 was connected with the prototype electronics in Figure 2 to perform a back wall echo test, comprising excitation of the transducer with an electrical pulse to produce ultrasound which propagates through approximately 73 mm mild steel and reflects off the back wall. The echo is then sensed by the same transducer in receive mode. Figure 4(a) shows an echo as viewed on an oscilloscope of the transducer output of a back wall reflection resulting from +/-3.3v excitation at 1.21MHz. The signal to noise ratio of the waveform is approximately 2.5 to 1.

To illustrate the capability of the electronics to generate an arbitrary electrical pulse excitation scheme, the transducer was excited with a single bipolar pulse. With each positive and negative pulse lasting for time duration of 410nS, corresponding to half a cycle at 1.21MHz, and amplitude ±3.3 V. Figure 4(b) shows a single back wall echo observed after filtering (but before correlation and post processing). via a band pass filter of pass band 0.5 to 5MHz to remove noise to have a peak-to-peak voltage of V_{pp} = 24 mV, or -48.7 dB compared to the excitation signal. After band pass filtering it can be seen that the received signal is well above the noise floor.

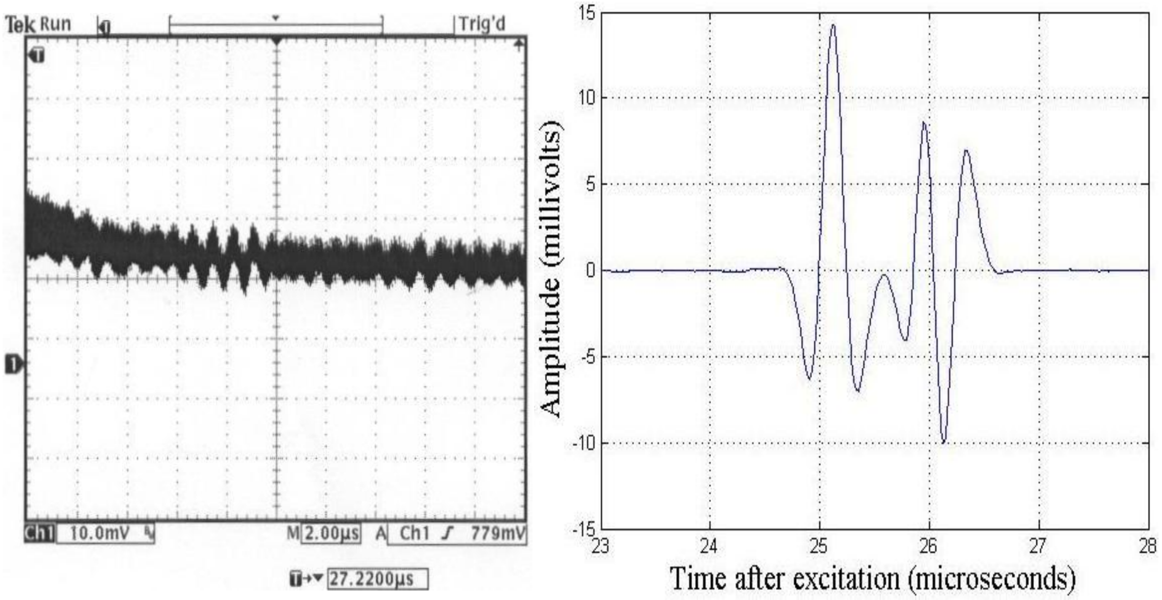

Figure 4(a). Filtered back wall echo in 73mm steel at +/-3.3V excitation and **4(b)**. Correlation of received samples following excitation on channel 1 and reception on channels 1-4.

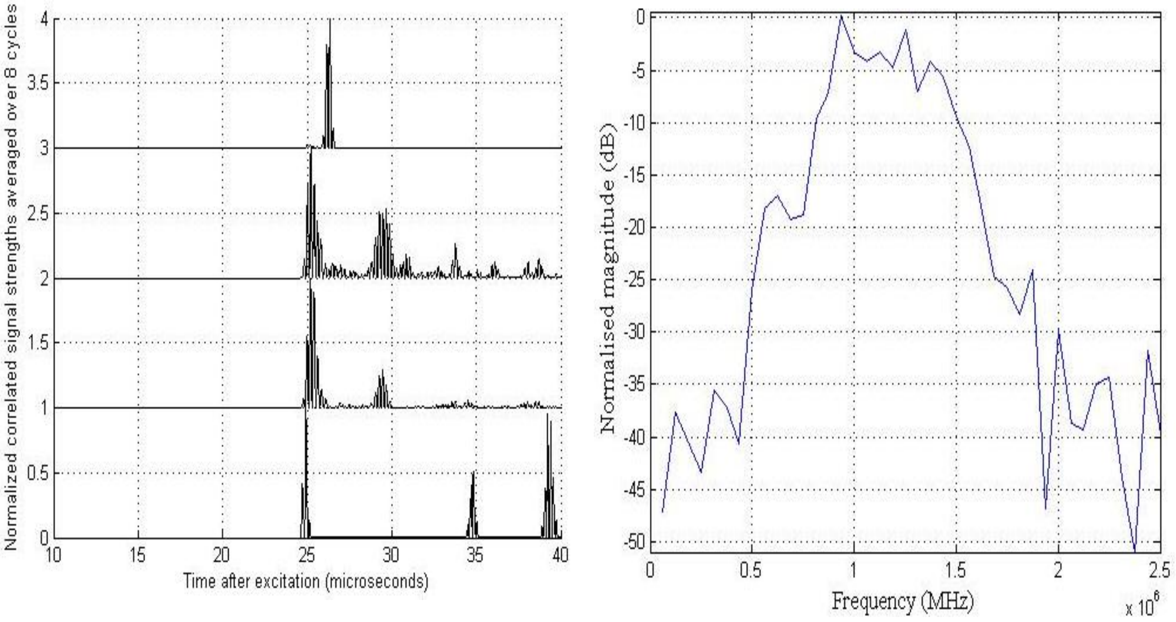

Figure 5(a). Correlation of received samples following excitation on channel 1 and reception on channels 1-4 and **5(b).** Frequency response of the transducer to the echo shown in Figure 4(b).

Figure 5(a) shows the correlated receiver data from 4 adjacent array elements numbered channels Rx 1 to 4 from the bottom upwards, following excitation on channel 1 (bottom most channel) at +/-3.3V in 73mm steel. The filtered received data streams on each channel are correlated by deriving the mean removed cross-correlation of the data and a template of the excitation sequence, in this case a single bipolar pulse. The correlations are then normalized to produce the plots shown, with the highest peaks being where the echo is detected. It can be seen that the correlations peak at slightly different times on each channel, corresponding to the increased distance the sound must travel to be detected by transducer elements situated further away from the element being excited. The correlation on channel 1 starts at about 24.5uS after excitation, as expected for sound travelling through 146mm of steel.

Figure 5(b) plots the frequency response of the reflected echo in Figure 4(b) and shows that for the frequency range 0.5 to 5 MHz, which is the one of interest once the received signal has been applied to the band pass filter, the normalised centre frequency is around 1.2 MHz and a dynamic range of approximately 75dB is evident.

A spectral analysis of the total system noise emitted comprising that emitted from the transducer, electronics and external noise pickup for the frequency range 0.5 to 5MHz yielded a background noise figure of approximately 720nV, largely due to the electronics. Peaks, due to the first and third harmonics of the transducer, of 3.74uV and 1.7uV were observed at 1.1MHz and 3.5MHz respectively. This demonstrated that despite very close coupling of transducer and electronics, the transducer still proved to be dominant.

CONCLUSIONS

The MOSAIC concept has been introduced here in the form of modular tiles designed to provide the necessary flexibility to operate in a wide range of applications without incurring substantial custom design costs. The system flexibility can be defined in terms of the array configuration, the number of elements in the array, the choice of the aperture, the frequency of operation and the excitation sequence used. All of these parameters are easily altered to give the user maximum flexibility.

The design methodologies behind the electronics and the preliminary transducer arrays have been outlined and preliminary results of back-wall reflection pulse-echo tests in steel have been presented. These demonstrate that sophisticated array electronics can fit within the footprint of a high frequency 16-element array and that signals with adequate SNR can be obtained, even with a tile which is not optimised for noise performance. Additional SNR gains are possible via the use of coded excitation waveforms and are easily implemented by reprogramming the FPGA. Further work needs to be done to document the system performance with regard to defect detection and characterization.

The solution documented within this paper is an intermediate one and consisted of the realization of 8 transmit / receive channels on a single circuit board 12mm wide and the FPGA housed on a separate board. 2 such analogue boards are used with a single 16 element array and a single FPGA board to create a ‘Midtile’. Work has been undertaken since to house all the electronics for a tile on a single circuit board, again, housed behind the array.

ACKNOWLEDGEMENTS

This project was funded by the UK Engineering and Physical Sciences Research Council. The electronics was developed in the Microsystems Technology Group at the University of Glasgow and the transducer was designed and fabricated within a group in the Scottish Universities Physics Alliance at the University of Paisley.

REFERENCES

1. K. Erikson, A. Hairston, A. Nicoli, J. Stockwell and T. White, "A 128x128 Ultrasonic Transducer Hybrid Array", in *Proc. IEEE Ultrasonics Symposium 1997*, October 5-8, 1997, Vol. 2, pp. 1625 – 1629.
2. K. K. Shung, and M. Zippuro, "Ultrasonic Transducers and Arrays", *IEEE Engineering in Medicine and Biology Magazine,* Vol. 15, Issue 6, Nov. – Dec. 1996, pp. 20 – 30.
3. D.J. Darlington, D.R. Campbell and D. Lines, "Reconfigurable FPGAs for Data Compression in Ultrasonic Non-destructive Testing", *IEE Colloquium on DSP Chips in Real Time Measurement and Control* (Digest No: 1997/301), 25 Sep 1998, pp. 2/1 - 2/4
4. M. Spies, "Optimisation of Mirrors for the Ultrasonic Inspection of Complex-Shaped Components Using Standard Transducers", *Review of Progress in Quantitative Nondestructive Evaluation, AIP Conference Proceedings*, Vol. 820, 6 March 2006, pp. 954 – 964.
5. I. Cicek, A. Bozkurt and M. Karaman, "Design of a Front-end Integrated Circuit for 3D Acoustic Imaging Using 2D CMUT Arrays", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 52, Issue 12, December 2005, pp 2235 – 2241.
6. I. Wygant, D. Yeh, X. Zhuang, S. Vaithilingham, A. Nikoozadeh, O. Oralkan, A. Sanli Ergun, G. Yaralioglu, B. Khuri-Yakub, "Integrated Ultrasound Imaging Systems Based on Capacitive Micromachined Ultrasonic Transducer Arrays", in *Proc. IEEE Ultrasonics Symposium 2004*, August 23-27, 2004, Vol. 1, pp. 391 – 394.
7. J.R. Talman, G.R. Lockwood, "Theoretical Evaluation of a 50 MHz Split Aperture Linear Phased Array", in *Proc. IEEE Ultrasonics Symposium 1997,* October 5-8, 1997, Vol. 2, pp. 1675 – 1678.
8. T. Misaridis and J. A. Jensen, "Use of Modulated Excitation Signals in Medical Ultrasound. Part I: Basic Concepts and Expected Benefits", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* Vol. 52, Issue. 2, pp 176 - 190, 2005.
9. W.A. Smith, "The role of piezocomposites in ultrasonic transducers", *IEEE Ultrasonics Symposium Proceedings*, pp. 755 – 766, 1989.
10. D. Robertson, G. Hayward, A. Gachagan, V. Murray, "Comparison of the performance of PMN-PT single-crystal and ceramic composite arrays for NDE applications", *Insight,* Vol. 48, No 2, pp 97 – 99, 2006.