Realizing dramatic improvements in the efficiency, sensitivity and bandwidth of ultrasound transducers

Philips PureWave crystal technology

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Summary

PureWave crystal technology represents the biggest breakthrough in piezoelectric transducer material in 40 years. PureWave's pure, uniform crystals are 85% more efficient for exceptional performance. PureWave technology enables improved penetration in difficult patients, the ability to image a wide array of patients with a single transducer, and reduced clutter for excellent detail of the endocardium and fine structures. Now, the new X7-2 transducer designed for pediatric Live 3D imaging combines PureWave with exclusive xMATRIX technology for the first time. When coupled with proprietary advances in microelectronics, PureWave's greater efficiency enables the X7-2 transducer's amazingly compact size.

Background

The piezoelectric material in an ultrasound transducer is a fundamental determinant of system image quality. Piezoelectric transducer elements are responsible for delivery of ultrasound energy into the scanned tissue and for converting returning ultrasound echoes into electric signals. Their coupling efficiency in converting electrical energy to mechanical energy or vice versa is a key determinant of image quality, Doppler sensitivity and penetration.

Despite many innovations over recent decades in signal processing and beamformer architecture, the same piezoelectric material, PZT (lead-zirconate-titanate) or PZT composites, has been the best-in-class material used for medical imaging for almost 40 years. This is a polycrystalline compound (ceramic) that, due to imperfect alignment of the individual dipoles, achieves at best only 70% polarization with corresponding constraints in the electromechanical coupling efficiency of the material.

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A new type of piezocrystal was discovered by Japanese and Russian scientists in the 1970s which showed improved electromechanical properties compared to PZT-type ceramics[1]. However, research on this type of piezocrystal was limited for many years due to the difficulty in growing the crystals (which were consequently limited in size to a few millimeters). Researchers, including Philips engineers, made fundamental technology breakthroughs in the 1990s in both crystal growth and crystal properties. The resultant piezocrystals exhibit a quantum improvement in electro-mechanical coupling compared to the traditional PZT-type ceramics[2-4].

An extensive Philips research program initiated in 1997 and partially funded by the United States Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA) explored possible medical applications of piezocrystals. This led to the development of PureWave crystal technology – an entirely new transducer technology designed with unique piezocrystals that offer significantly improved efficiency and bandwidth compared with conventional PZT ceramics[4-5].

The introduction of the S5-1 transducer in 2004 combined PureWave technology with other advances in transducer design (uniquely designed matching layers and backing material) to set a new benchmark in 2D ultrasound imaging performance as well as color and Pulsed Wave Doppler sensitivity. The next significant challenge for ultrasound transducer design is the combination of PureWave crystal technology with 3D xMATRIX transducers. This has now been achieved with the release of the new X7-2 transducer, bringing the image quality advantages of PureWave technology to 3D and allowing new levels of anatomic detail and clarity in both transthoracic evaluation of congenital heart disease and epicardial imaging for interventional procedure guidance.

Technology

PureWave Crystals vs. PZT Ceramics

To create an overall piezoelectric effect, materials such as PZT ceramics must be subjected to a poling process (application of an external electric field) to align dipoles within polycrystalline materials. In conventional PZT ceramics, due to the constraint of the grain boundaries, only a fraction of dipoles can be aligned by an electric field and not all dipoles contribute to the acoustic response of the material.

PureWave crystal material, however, is more uniform and exhibits fewer defects, lower losses and no grain boundaries. When these crystals are poled at the preferred orientation(s), near perfect alignment of dipoles (~100%) can be achieved (see Figure 1) resulting in dramatically enhanced electromechanical properties.

Crystal Growth Comparison

To prepare conventional PZT ceramics, fine powders of the component metal oxides are mixed and then heated to form a uniform powder. The powder is mixed with an organic binder and baked into a dense polycrystalline structure.

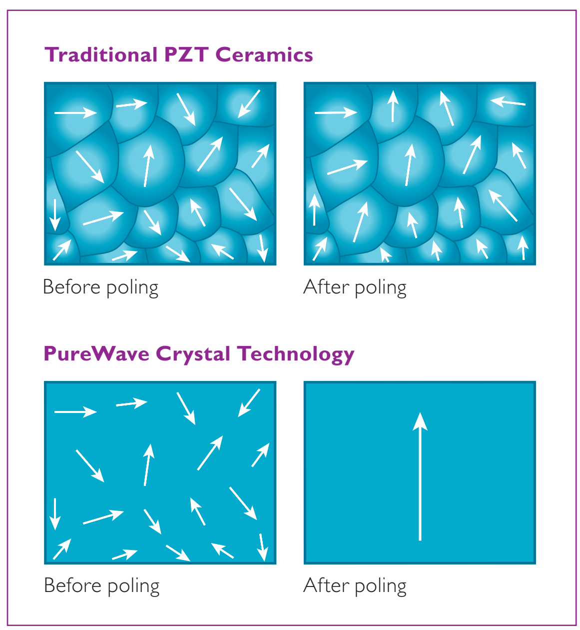


Figure 1. Dipole reorientation during poling of PZT vs. PureWave crystal

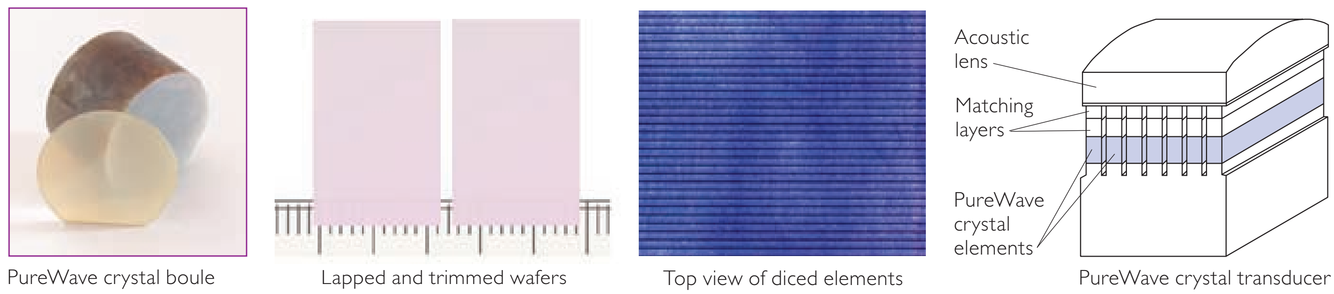


Figure 2. Element manufacture from PureWave crystal boule

To produce PureWave crystals, the fine ceramic powder is formed using a process similar to PZT powders, however the rest of the process is unique. The powder is then melted into liquid in a platinum crucible at 1400˚ C using a specially designed high temperature furnace with a precisely controlled temperature profile. To nucleate the crystal from the melt at the desired orientation, a seed crystal is pulled (or drawn) away from the melting zone slowly (less than 1 mm/hour) and the crystal is grown layer by layer atomically to form a homogeneous crystal "boule" or cylinder. Boules are orientated along the desired crystallographic orientation(s) to maximize the crystal properties and then sliced into multiple wafers. Philips has been at the forefront in innovating piezocrystal technologies by developing crystal growth and post processing techniques for fabricating large homogeneous crystals for medical imaging applications (see Figure 2). This breakthrough approach from crystal growth to transducer design is unique to Philips.

Compared to conventional transducer material, the PureWave crystals are purer, more uniform, have lower losses and are able to transfer energy with greater precision and efficiency. PureWave crystals exhibit very high electromechanical coupling factors as demonstrated by the following statistics:

- The efficiency of converting electric-to-mechanical energy improves by as much as 68-85% (as shown in Figure 3) compared to PZT ceramics currently used in ultrasound transducers.
- PureWave crystals exhibit ten times the strain (or ability to change thickness under an electrical field, as shown in Figure 4) compared to traditional polycrystalline PZT-type ceramics. They are, therefore, ideal for use in ultrasonic imaging applications.

Material	Sliver	Rod
PZT Efficiency	0.39	0.52
PureWave Crystal Efficiency	0.72	0.87
Efficiency Improvement with PureWave Crystals	85%	68%

Figure 3. Efficiency comparison of PZT ceramic vs. PureWave crystal

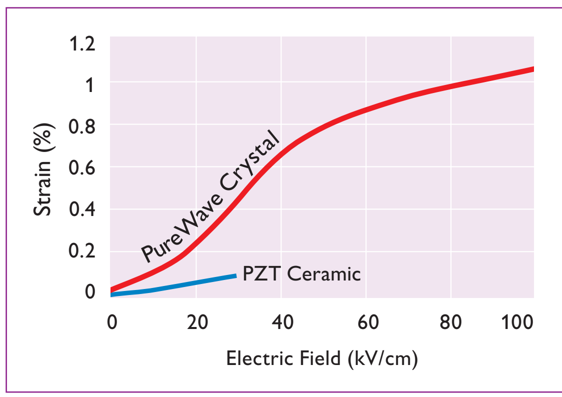
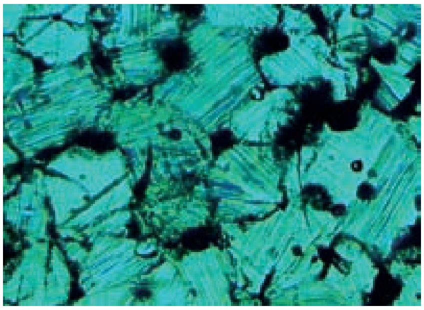
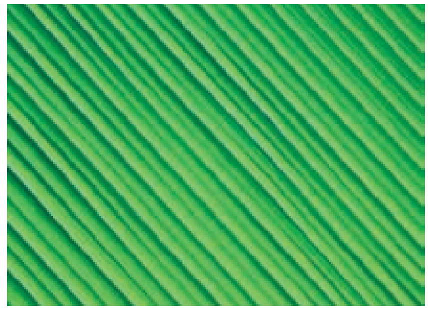


Figure 4. Strain behavior of PureWave crystals vs. traditional PZT-type materials



Imperfect, multi-crystalline, randomly orientated grains



Perfect atomic level arrangement, uniform, no grain boundaries

The parallel lines showing in both PZT and PureWave crystals are the ferroelectric domains. When the domains are properly aligned, they give better piezoelectric efficiency.

Transducer Design Implications

The current family of Philips transducers already exhibits impressive bandwidth and sensitivity as compared to the rest of the ultrasound industry. Replacing the presently used PZT materials with the new PureWave crystals achieves significant additional gains in bandwidth and sensitivity. Using PureWave crystal technology in conjunction with precisely engineered multiple matching layers and backing material, it is now possible to cover the frequency range of two best-in-class broadband transducers with a single probe.

The perfect arrangement of atoms in PureWave piezocrystals and their superior strain energy density over conventional piezoceramics make them an ideal choice in the quest for miniaturization of 3D xMATRIX transducers. This is exemplified by the new X7-2 xMATRIX transducer, which offers PW Doppler in an impressively compact form factor as well as excellent 3D image quality and color sensitivity. The X7-2 comprises 2,500 active elements for fully sampled, high-resolution 3D volumes yet its footprint is small enough to allow intercostal access in pediatric applications and it uses an extremely lightweight, ultra-flexible cable.

Application Advantages

PureWave crystal technology with extended transducer bandwidth and sensitivity offers significant performance advantages, particularly in penetration and imaging resolution. The ability to gather, process and display more diagnostic information results in images of remarkable clarity and fine detail with greater uniformity throughout the entire image field.

PureWave and breakthroughs in ASIC design facilitated the miniaturization of the X7-2 transducer.

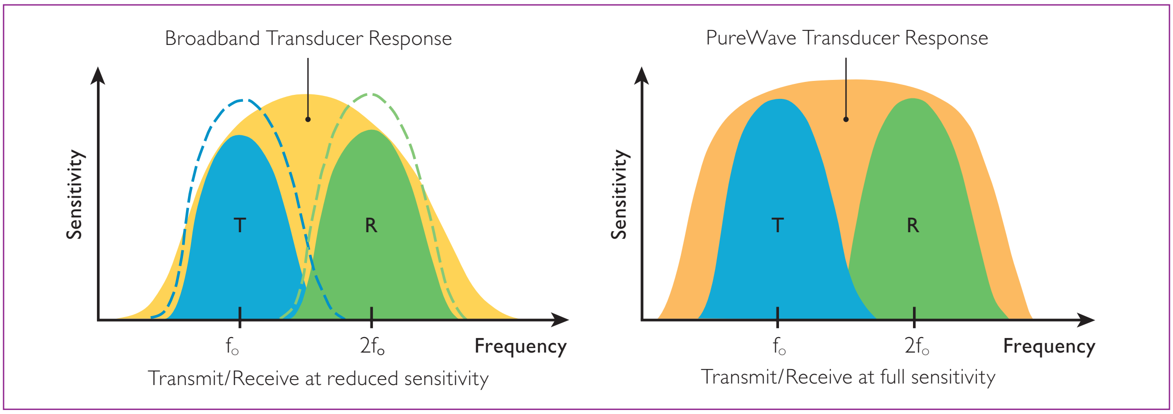


Figure 5. Comparison of conventional harmonic imaging with PureWave transducer sensitivity/bandwidth

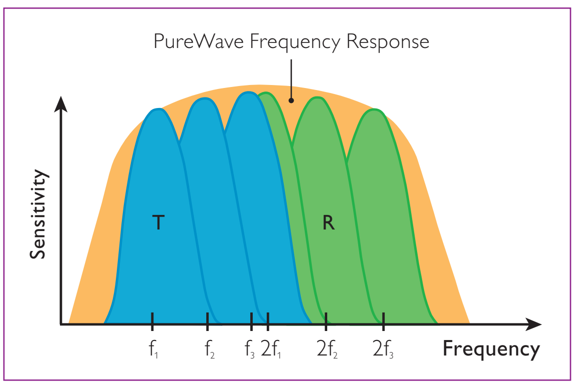


Figure 6. Multiple pair second harmonics for different types of applications

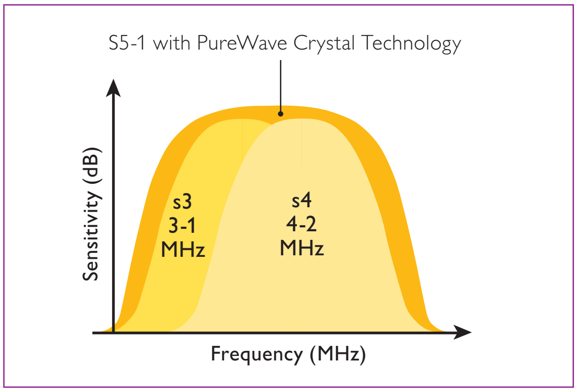
Particular benefits are noted in technically difficult studies, allowing successful delineation of the entire endocardial border in a higher percentage of patients. It also provides benefits in cost efficiency as well as workflow by reducing the need to change transducers during examinations.

PureWave crystal technology allows better use of harmonics, presenting additional options for signal processing. The greater sensitivity across a wider range of frequencies afforded by PureWave crystal technology provides the flexibility to transmit and receive harmonic frequencies at full sensitivity level for enhanced harmonic performance. Figure 5 shows the comparison of traditional broadband technology to the PureWave crystal technology for harmonic applications.

Furthermore, transducers with PureWave crystal technology can be operated at full sensitivity for multiple pairs of transmit/receive harmonic frequencies (see Figure 6). Superior sensitivity at multiple second harmonic frequencies means that clinicians can select from a wide harmonic frequency range to address different imaging needs.

PureWave crystal technology provides significant benefits in both tissue and contrast harmonic applications. In tissue harmonics, the increased sensitivity provides improved penetration and border delineation, achieving results in difficult patients that could only otherwise be attained with LVO contrast. The resulting harmonic images have significantly reduced clutter with greatly enhanced structural detail as seen in the resolution of the endocardium and fine structures such as valves and chordae tendinae. The wider bandwidth and superb coverage of lower frequencies from the PureWave crystals provide the main benefit for contrast harmonics. The higher sensitivity allows clinicians to detect bubbles more easily.

In contrast harmonic imaging the S5-1 offers superb endocardial border delineation using LVO contrast. Clinicians have reported that the sensitivity of the S5-1 transducer has allowed them to work with 30-50% less contrast, thereby achieving obvious cost savings and patient dose reduction.



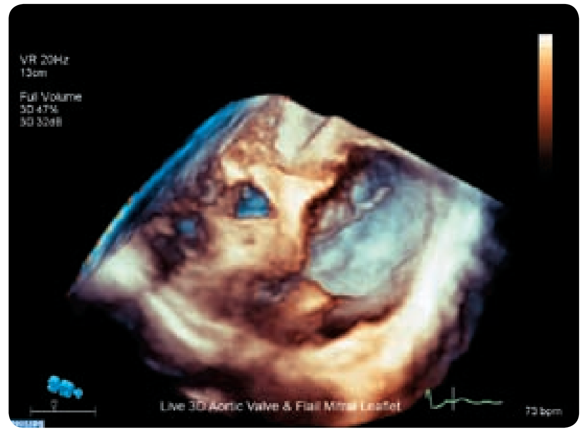


Figure 7. Frequency coverage of PureWave crystal technology vs. state-of-art existing broadband transducer technology

The S5-1 transducer with PureWave crystal technology perfectly demonstrates the concept of a "one-probe" solution, spanning the frequency ranges of two state-of-the-art broadband probes (see Figure 7). This means that one transducer can be used for a greater range of patient types, thereby offering significant workflow advantages along with the performance and image quality enhancements already discussed. Additionally, it opens the door for advanced applications currently not available using conventional broadband transducers.

In addition to covering a wider range of frequencies than current transducers, the S5-1 also provides significantly better sensitivity at the color flow and spectral Doppler frequencies.

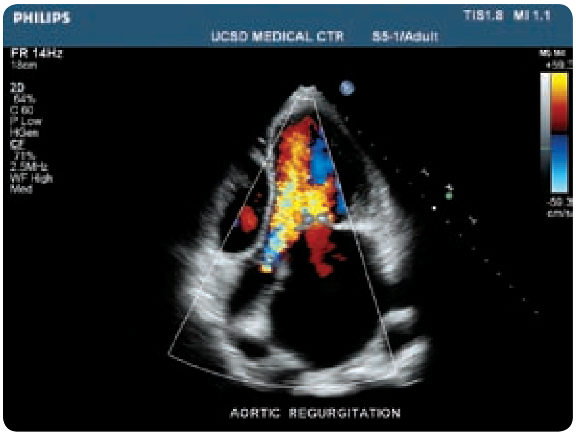
The use of PureWave technology in the X7-2 xMATRIX transducer introduces a new class of near field imaging performance to Live 3D echo. This Live 3D transducer is optimized for neonatal scanning and for epicardial imaging, setting a benchmark for assessment of congenital heart disease and for guidance during interventional procedures.

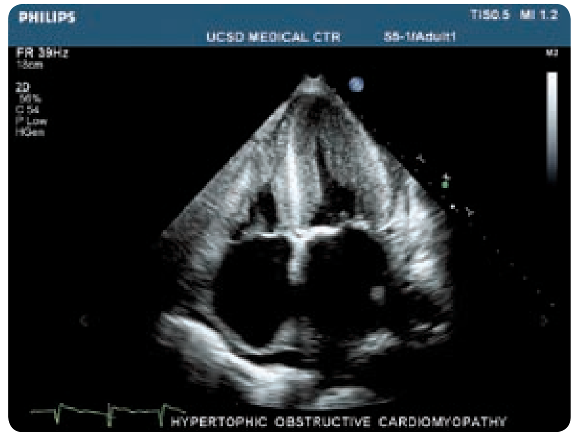
In particular, complex multi-faceted anomalies such as Ebstein's can be more directly evaluated with the same detail of anatomic interrogation that a surgeon might achieve.

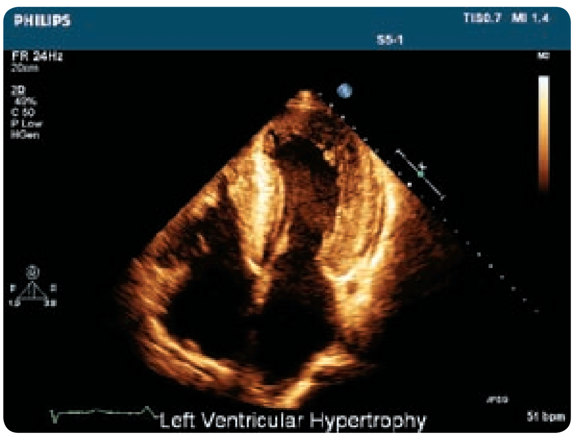
PureWave Crystal Technology for all Ultrasound Applications

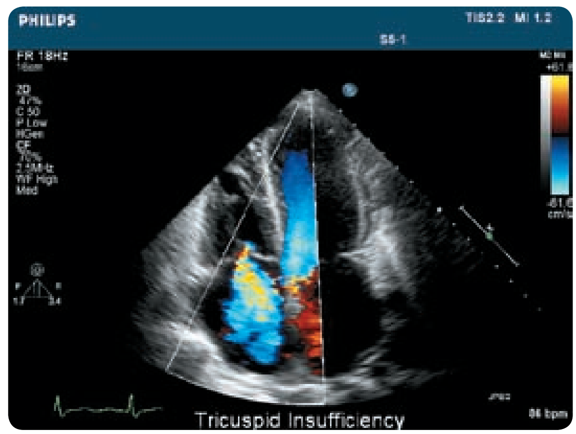
The performance advantages of PureWave crystal technology are not just confined to low frequency cardiac applications. Sensitivity and efficiency gains are evident in the design of other transducers such as linear and curved linear transducers, realizing electromechanical coupling efficiency improvements of 68-85% respectively. PureWave crystal technology has brought transducer design technology to a new level.

The latest realization of PureWave technology is in 3D transducer design, allowing new levels of miniaturization, image quality and the flexibility to support multiple imaging and Doppler modes.









Conclusion

PureWave crystal technology provides dramatic improvements in the efficiency, sensitivity and bandwidth of ultrasound transducers. This breakthrough has allowed the development of next generation 2D transducers such as the S5-1 which has set new benchmarks in 2D imaging resolution, more sensitive contrast harmonics, improved color flow sensitivity, enhanced endocardial border delineation, and superb low frequency tissue harmonics. The new X7-2 xMATRIX transducer provides the next significant milestone in PureWave technology and is a concrete step closer to the vision of a single transducer offering remarkable performance for the complete range of 2D, 3D and Doppler applications.

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