Journal of Intelligent Engineering and Informatics, Vol 1, 2026

Broadband Underwater Acoustic Sensing Using Pressure-Stable Relaxor Single-Crystal Hydrophones: A Review

Jeevabharathi Tharanitharan[1], Remya[2],*

[1]Mainefhi College of Engineering and Technology, Department of Electrical and Electronics Engineering, Eritrea.

[2]Vidhya academy of science and technology, Department of Electronics and Communication Engineering, Thrissur, India

Mail id: remya826@vidyaacademy.ac.in

Abstract- Relaxor-ferroelectric single crystals may be used to increase hydrophone sensitivity and a wide bandwidth, however, in response to loading conditions, pressure, temperature, bias and cyclic loading, the domain state in the single crystals vary. This survey covers pressure stable broadband receivers using PMN-PT, PIN-PMN-PT, PZN-PT, doping and polymer composites. There are few international journal papers from the years 2015 to August 2026 based on crystal chemistry and growth, domain engineering, composite connectivity, receiver architecture, packaging, and qualification evidence. The fabricated tank-tested composites bring finite-element concepts and transmitter-only demonstrations to a halt. The synthesis states that main challenge to be faced in synthesis is maintaining calibrated receiving sensitivity and low self-noise from combined pressure-temperature-bias histories. Practical validation protocol and a deployment evidence ladder are proposed.

Keywords- Relaxor ferroelectric; piezoelectric single crystal; hydrophone; underwater acoustic sensing; PMN-PT; PIN-PMN-PT; deep-sea pressure; piezocomposite.

I. INTRODUCTION

Radio waves experience severe attenuation to travel long distances in sea water, thus underwater acoustic sensing is needed for sonar, underwater environmental monitoring, navigation, communication and inspection. The hydrophone picks up a small acoustic pressure and translates it into an electrical signal; a vector sensor additionally provides the direction of the particle-velocity. Single crystals of relaxor-ferroelectric type possess much more high values of electromechanical coupling and the piezoelectric coefficient, particularly single crystals in the neighborhood of morphotropic phase boundary, such as PMN-PT and PIN-PMN-PT. Their anisotropy also allows the existence of longitudinal, shear, and face-shear modes which can be difficult to obtain from an isotropic ceramic [1] – [3]. There are 3 reasons why interest has picked up. The first is the improvement in the size and uniformity of the crystals by continuous-feeding Bridgman growth. Diplomatically controlled, doping is being done [24]-[26]. Secondly, the acoustic impedance of dice and insert, conformal and dual-connectivity composites is reduced while at the same time ensuring good crystal response [9],[10],[16],[20] and [21]. Thirdly, small, self-contained systems require increased bandwidth and increased reception sensitivity without increasing the aperture and/or electronic power.

The most recent prototypes to be developed include thickness-mode hydrophones [5], vector sensors [2, 3, 7], pressure-tested hydrophones [6], and deep-sea face-plated composites [8] or sea-tested self-powered beacon [22]. There is a tough choice to make when it comes to the attraction. A near threshold behavior of a multidomain engineered state to a phase or polarization instability is essential for achieving high response. Domain walls can be shifted, or phase fractions modified, under the influence of hydrostatic pressure, uniaxial preload, temperature, electric bias, cycling. Sensitivity after poling in a laboratory may therefore change after packing and after descent, long dwell or after repeated operation. Face plates either stiff or soft polymer can be used to protect the crystal but may reduce compliance, or to achieve good acoustical match which can suffer from creepy face plate, water uptake, and temperature sensitivity. Using only reported voltage sensitivity and/or bandwidth figures alone cannot demonstrate whether or not a design will maintain its calibration at depth. Available literature is inadequate as yet for providing the needed synthesis. Tian et al. relate the characteristics of PMN-PT to

Journal of Intelligent Engineering and Informatics, August 2026, Volume 1, Issue 1, Pages 1-13
Corresponding author. E-mail address: remya826@vidyaacademy.ac.in
Received 9 July 2026; **revised** 10 August 2026; **accepted** 18 August 2026; **published** 25 August 2026.
© 2026 Scholarly Horizon Publication. All rights are reserved including those for text and data mining, training of AI and similar technologies. This is an open access article under the Creative Commons Attribution-Non-Commercial International (CC BY-NC 4.0) License

two applications for underwater transducers [1] but their paper is an application study and not a systematic review.

The high-power projector characteristic has been stressed by Finkel et al. when discussing transduction near instability [30] and not (passive) receiver calibration under deep sea conditions. This search of the journal literature has not found any comprehensive survey which uses one deployment test to connect chemistry, domain state, composite geometry, receiver architecture, package stress and evidence of environment. It is this right gap that gives the novelty in this paper. Elsevier, Wiley, AIP, IOP, MDPI, Taylor and Francis, Springer Nature, and the American Ceramic Society publishers' databases and IEEE Xplore were selected and structured searches were performed for the review. Concatentating terminology related to piezoelectric or relaxor single crystal to underwater; hydrophone, vector sensor, acoustic transducer, pressure, temperature, composite, PMN-PT, PIN-PMN-PT, and PZN-PT hooks up studies on the devices to growth and domain stability evidence.

The taxonomy is based on the development chain and not on dates of publications. It has six interrelated groups: crystal chemistry, growth and doping; crystallographic cut, domain engineering and poling; composite connectivity and scalable shaping; scalar and vector receivers architecture; acoustic matching, encapsulation and preloading; and pressure temperature bias qualification. Evidence is developed between material-only measurement and finite-element simulation, fabricated tank testing, environmental-chamber testing, and sea trials. The purpose of this structure is to distinguish between desired gains due to the effects of the active crystal from undesired gains due to mechanics or electronics; it also makes it impossible for the transmitting answer of a structure to be used as evidence for low-noise receiving performance. The critical research question is that of a pressure-temperature-bias-stable receiver that maintains sensitivity, bandwidth, directivity and self-noise after exposure to realistic history.

The solution cannot be obtained through other peak value measured under room conditions, but with the coupled material and package models. The most helpful near term direction for the composite is face plated or mechanically de-coupled with third generation doped crystal, with built in monitoring of temperature and pressure and the ability to check the state of the built-in domain by using the descent/dwell/thermal cycling/recovery method for calibration. The future studies should also be reported by sample-to-sample variation, ageing, noise spectra, cross axis response and failure modes. This survey provides exact boundaries, a sixfold taxonomy of materials-to-deployment, native equations for the same receiver metrics studied in other works and a clear boundary between achievable prototypes and various concepts to be investigated via simulation. The design flow is organized in the form of Figure 1, the scope, methods, evidence, metrics and readiness are summarized in Tables 1-5, and the identified stability problem is broken down into testable research tasks in the form of the final agenda. These sections have a uniform materialially deployed argument.

II. SCOPE AND REVIEW FRAMEWORK

A. RESEARCH QUESTIONS AND EXACT BOUNDARIES

There are three questions in the survey. Which material and structure make a relaxor single crystal to a sensitive broadband underwater receiver? What are the environmental conditions which result in calibration loss? Of the reported approaches, what are the ones that have evidence sufficient for promise, not just simulation? These questions shift the focus to both the performance of the device as well as the quality of the evidence. The active phase is confined to bulk, single crystal or single crystal-like phases of relaxor-ferroelectrics: PMN-PT, PIN-PMN-PT, PZN-PT and Mn doped and Nd doped relaxor-ferroelectric. When a receiver-relevant result is measured the included devices include scalar hydrophones, vector sensors, and dual use underwater transducers. Projector studies are only provided if they are vital to the receiver design for reciprocal construction, high field behaviour, pressure response or thermal behaviour. An ordinary piezoceramic vector hydrophone is still kept as an architecture benchmark to prevent structural gain from being falsely attributed to the crystal.

Applications range from low frequency bender and vector sensors to multi hundred kHz composite hydrophones and are based on acoustic sensing in water. Unless a manufacturing method that can be readily transferred to composite construction beneath the water is clearly identified, MHz biomedical imaging and nondestructive testing are not included. Thin-film MEMS, PVDF-only sensors, triboelectric hydrophones (or optical hydrophones), post-receiver sonar processing, localization algorithms and underwater communication networks are beyond the scope. The time boundary is 2015–4 August 2026 and the evidence set is restricted to English language ĐOI journal articles. Not all underwater piezoelectric mic transducers but the focal emerging sub-field is pressure-stable broadband relaxor single-crystal receiving. Pressure-stable: A test to evaluate loss in calibrated sensitivity and directivity of a receiver following a specific pressure, temperature, preload, bias and dwell history.

Broadband applies to the sensitivity, and a wide transmitting band alone is not a valid definition of broadband. This leaves their conclusions testable with the operational definitions.

B. LITERATURE SEARCH AND VALIDATION

Material names and abbreviations as well as water and hydrophone response were tied in with hydrophone, underwater acoustic, vector sensor, receiving sensitivity, deep sea, hydrostatic pressure, composite, face plate, and transducer. The searches were carried out with growth, doping, domain switching, coercive field, temperature and fatigue to catch the mechanisms which device titles do not. Checks of Citation chaining from [1] [2] [5] [6] [8] and [30] were used to find related crystal and composite studies. Records were screened based on reported methods and evidence as well as by title and abstract. A paper was deemed to be a part of the final set if it involved measuring a single-crystal underwater receiver; measuring underwater a component or transducer of a receiver; quantifying behavior of an element or transducer with respect to pressure, temperature, field, fatigue, or stress, necessary for qualification; or documenting scaling growth or fabrication. Only papers containing general talk about piezoelectrics were excluded.

The method is not statistical meta-analysis but is structured critical survey. The following effects are so different in center frequency, aperture, acoustic load, preamplifier, reference pressure, bandwidth definition and test tank that a pooled effect size cannot be calculated. Both papers are instead coded based on active material, domain/cut, composite connectivity, operating mode, receiver type, measured metric, environment, and evidence level. Reported numerical enhancements are only relevant within the study, as baseline and test settings must be the same.

C.COMPARISON WITH EXISTING REVIEWS

A new survey is needed as shown in Table 1. The application study [1] gives the reasons why the PMN-PT is better than the PZT and gives examples of transducers; and the review [30] gives an explanation on the instability-assisted transduction, mainly for projectors. Both provide a receiver centered taxonomy that takes the path a crystal follows from growth to packaging to pressure qualified calibration. The present survey is limited to that "small" intersection and does not presume to substitute for more general surveys of piezoelectric materials, of sonar, or of underwater transducers.

TABLE 1. Exact survey boundary and position relative to the nearest synthesis papers.

Item	Coverage	What remains outside	Role in this survey
Tian et al. [1]	PMN-PT properties; two underwater transducer examples	No systematic receiver taxonomy or environmental evidence ladder	Nearest material-to-device application study
Finkel et al. [30]	Transduction near crystal instability; strong projector focus	Not a passive deep-sea hydrophone qualification survey	Mechanistic adjacent review
Primary set [2]-[29]	Growth, domains, composites, devices, and environment	Results use different metrics and evidence levels	Coded by one material-to-deployment framework
This survey	Pressure-stable broadband single-crystal receivers	Excludes general sonar, thin films, optics, and signal processing	Links design choice, metric, and deployment evidence

D. CODING AND EVIDENCE RULES

There is no differentiation between the evidence based on model complexity, rather the strongest model completed will be used to grade evidence. Level 0: Material constants, Analytical concept (idea). Level 1: Finite-element or equivalent-circuit simulation or simulation with no receiver prototype. Level 2 is a fabricated specimen or device characterized in air or by its impedance. The water-tank receiving measurement (level 3) is calibrated. Level 4 incorporates also controlled pressure, temperature, preload, or long duration cycling. ANT level 5 is a sea trial / deployed operation. Transmitter-only tank results is still valuable construction evidence which may not be promoted to receiving validation. Coding is also able to distinguish between material, structure, and electronics. The receiving voltage sensitivity will be greater if one of the following is used: a higher piezoelectric voltage coefficient, mechanical amplification, lower capacitance, transformer or matching-network gain, or if an active preamplifier is used. If these sources are not separated from the experiment, it is awarded a "material result" rather than a "system result" for the paper. For bandwidth, the same goes: a matching layer, backing, face plate, multiple resonance, or an electrical network can make a response wider, but will not affect its intrinsic crystal coupling.

III. MATERIAL-DEVICE MODEL AND INNOVATIVE CHALLENGE

A. DEVELOPMENT AND QUALIFICATION FLOW

The materials path used for the survey and to deploy the materials is illustrated in Figure 1. The uniformity of set, the defect chemistry, the coercive field and the size of the available boules are set by chemistry and growth. These properties are converted into an engineered domain state by cut and poling. Acoustic impedance, capacitance, modal coupling and manufacturability depends upon connectivity and shape. In receiver architecture, pressure or particle motion are converted into strain. Preload and environmental boundaries are then imposed by packaging. The final evidence gate considers the question of whether or not the calibration can cope with realistic pressure-temperature-bias history. PowerPoint version provided with the shapes, labels and straight connectors.

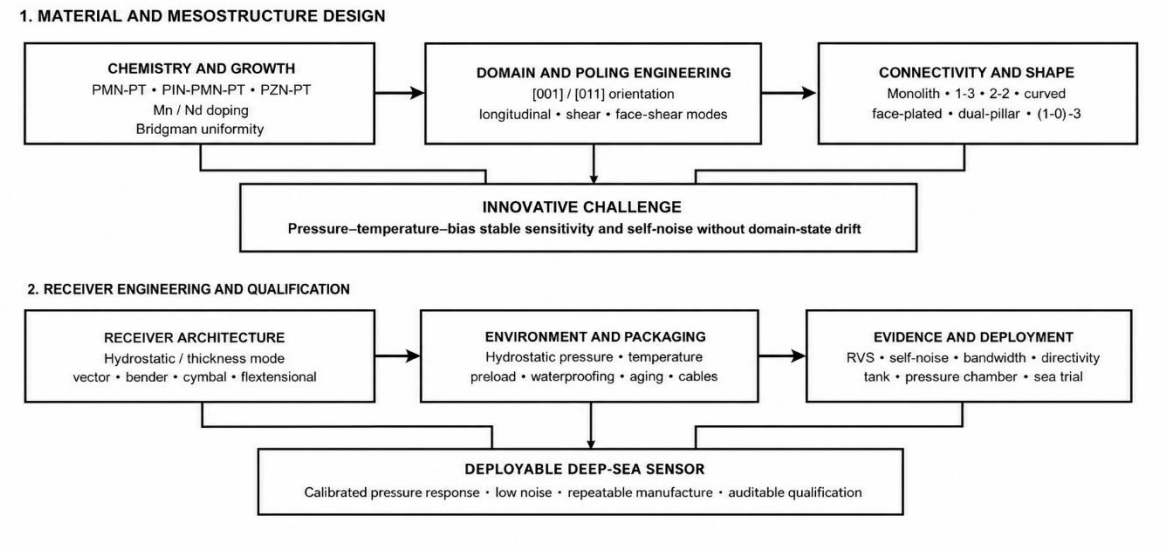


Figure 1. Material-to-deployment flow

B. MATERIAL RESPONSE AND HYDROSTATIC PERFORMANCE

The linear piezoelectric constitutive relationship relates electric displacement and strain to stress and electric field. It is a small signal model, and needs to be extended to include domain switching, phase change, creep, and hysteresis with more state variables. What is important to note here is that it demonstrates that the constants of the crystal are not arbitrary with respect to mechanical boundary conditions.

$$D=dT+\epsilon^{T}E, \qquad S=s^{E}T+d^{T}E \tag{1}$$

In the case of a hydrostatic receiver, the longitudinal and transverse charge contributions are added together. The fact that a high value of piezoelectric charge alone is not enough is manifested in the expression of the hydrostatic charge coefficient, voltage coefficient and figure of merit (2). Crystal cutting, domain state and composite clamping is every effective term.

$$d_{\mathrm{h}}=d_{33}+d_{31}+d_{32}, \qquad g_{\mathrm{h}}=\frac{d_{\mathrm{h}}}{\epsilon_{33}^{T}}, \qquad F_{\mathrm{h}}=d_{\mathrm{h}}g_{\mathrm{h}}=\frac{d_{\mathrm{h}}^{2}}{\epsilon_{33}^{T}} \tag{2}$$

C.RECEIVER PERFORMANCE CHARACTERISTICS

When receiving the voltage sensitivity, it is necessary to know frequency and environment. The formula (3) represents reference open circuit voltage and incident acoustic pressure with a reference of one volt/one micropascal. The gain of the preamplifier has to be removed or declared. An off-resonance baseline may be absent in a resonance peak which makes a narrow receiver look broadly sensitive.

$$M_V(f,P,T)=20\log_{10}\left(\frac{|V_{\mathrm{oc}}(f,P,T)|}{p_{\mathrm{ac}}}\right) \tag{3}$$

Self-noise is the quietest pressure which can be detected. The noise-equivalent pressure is determined via equation (4), the measured voltage transfer function, and voltage-noise spectral density. There are few studies that report this quantity, but the sensitivity benefit at the crystal level can be erased by the dielectric loss, cable noise, leakage, amplifier current noise and package vibration.

$$\mathrm{NEP}(f,P,T)=\frac{\sqrt{S_V(f,P,T)}}{|V_{\mathrm{oc}}(f,P,T)/p_{\mathrm{ac}}|} \tag{4}$$

The fractional minus three decibels bandwidth is measured as the minus 3 dB bandwidth from its lower to higher frequencies and expressed by equation (5). If the band is mentioned then it must be specified whether the band corresponds to transmitting voltage response, receiving voltage sensitivity, conductance or pulse echo. Under controlled linear and passive environments only the reciprocity between these quantities is considered.

$$B_{-3\ \mathrm{dB}}=\frac{f_H f_L}{(f_H+f_L)/2},\qquad \left|M_V(f)-M_{V,\mathrm{ref}}\right|\leq 3\ \mathrm{dB} \tag{5}$$

D.ENVIRONMENTAL STABILITY AND DOMAIN RELIABILITY

The worst retained sensitivity in the environments set should be used to evaluate a deep-sea receiver, not necessarily just the room-pressure maximum. Normalization of the pressure-temperature transfer function is done by equation (6). Hysteresis needs to be accounted for with the set comprising descent, dwell, thermal cycling and recovery.

$$R_{\mathrm{env}}=\min_{(P,T)\in\Omega}\frac{10^{M_V(f,P,T)/20}}{10^{M_V(f,P_0,T_0)/20}} \tag{6}$$

The coercive field as expressed in (7) is a limit also for electrical drive and bias, which would both be below that value for the determined environment. The acoustic field for passive hydrophones is small, but the poling history, charge amplifiers, leakage, electrostatic offsets and dual-use transmitting pulses can decrease the margin. This is why it is not safe to rely on a single room temperature limit, as is evidenced by stress induced domain evolution [27] and [28] and temperature-frequency dependence of coercive field [29].

$$E_{\mathrm{drive}}+E_{\mathrm{bias}}<E_c\left(P,T,\dot{E}\right) \tag{7}$$

E. CALIBRATION STABILITY UNDER COUPLED CONDITIONS

The novel challenge set forth herein is designing a broadband single-crystal receiver whose calibrated sensitivity and self-noise are both stable combined pressure-temperature-bias histories. The challenge is tougher than surviving a target pressure. It queries surfaces as to whether domain configuration, polymer constraint, face-plate stress, bonding, electrode contact and front-end impedance revert to a known state. A useful target would specify a band, a pressure range, a temperature range, a dwell time, a permitted sensitivity drift, a permitted directivity error and a noise limit pre-fabrication. What is needed is a practical research platform that employs the same face-plated 2-2 or 1-3 geometry used in PMN-PT for Mn:PIN-PMN-PT; add fiber-optic or resistive pressure-temperature witnesses; allows for in-situ impedance and low-level acoustic calibration during pressure cycling. Domain diagnostics are available at the beginning and the end of the chamber sequence by using X-ray or optical domain diagnostics. This design would relate mechanism of the materials [27]-[29] to the deep-sea effect [8] and they would separate reversible package loading and irreversible domain change.

IV. CLASSIFICATION OF EXISTING APPROACHES

In table 2 all the six branches have been summarized before giving detailed synthesis. Branches are dependencies: a device architecture cannot be evaluated independently of the crystal state, composite constraint, package stress and evidence level.

TABLE 2. Material-to-deployment taxonomy for relaxor single-crystal underwater receivers.

Taxonomy branch	Main design lever	Expected gain	Main failure risk	Representative refs.
Chemistry and growth	PMN/PIN/PZN; Bridgman control; Mn/Nd doping	Coupling, boule size, stability window	Composition drift, defects, property spread	[24]-[26]
Domain and poling	Cut, engineered domains, poling, shear mode	Anisotropic response and direction sensing	Stress switching, fatigue, depoling	[2], [3], [7], [19], [27]-[29]
Composite connectivity	2-2, 1-3, dual-charge, curved/conformal forms	Lower impedance, wider band, larger aperture	Kerf error, polymer creep, stress concentration	[5], [8]-[10], [16], [17], [20], [21]
Receiver architecture	Thickness, bender, vector, flextensional, Tonpilz	Sensitivity, direction, compact low-frequency	Parasitic modes, cross-axis error, resonance	[1]-[8], [13]-[15], [17]-[19], [22]

		response		
Matching and packaging	Face plate, backing, matching layer, shell, preload	Protection, modal control, usable bandwidth	Added stiffness, sealing failure, noise drift	[1], [6], [8], [11]-[15], [23]
Qualification evidence	Tank calibration, chamber cycling, sea trial	Retention and field confidence	Transmit proxy or endpoint-only test	[2]-[8], [15], [22], [27]-[29]

A. CRYSTAL COMPOSITION AND MATERIAL DEVELOPMENT

PMN-PT combines very high coupling and sensitivity, with limitation on thermal and field margins imposed by its coercive field and transition temperature. By introducing PIN-PMN-PT into the material, the stability window can be expanded, and domain wall pinning and reducing its response loss by introducing the Mn acceptor doping. Regular solution of the drift of composition and limitations of a boule length are the goals of continuous-feeding Bridgman growth in case of PMN-PT and PIN-PMN-PT applications [24]. In [25] Mn doped PIN-PMN-PT with the same growth method is characterized and ND doping in PMN-PT aims for ultra-high piezoelectricity [26]. Doping cannot therefore not be a universal improvement as the stability and/or power handling capabilities can be enhanced at the expense of the small-signal compliance and/or the anisotropy may be altered. Styles that are useful for receivers include spatial maps of the following useful material properties in the boule: composition, dielectric loss, coercive field, piezoelectric constants, transition temperature, and defect-related aging. Reporting only the best coupon makes the envelope yield and the calibration spread. Choices of material should be made after defining the preload, operating temperature and electric boundary condition, which will shift the domain and phase landscape.

B. CRYSTAL ORIENTATION AND DOMAIN CONTROL

The crystallographic cut controls which large coefficient and mode becomes available. The thickness-shear operation is used for compact vector accelerometers [2, 3] and the compressive PMN-28PT elements in [7] are optimized for a vector sensor. Another path to small transduction at low frequency is the face-shear excitation [19]. Stresses can reorient domains and alter the effective constants, but it is sometimes possible to create strong anisotropies in hydrophones by engineering the [011] domain states [5]. The mechanistic evidence is quite conclusive. There is a difference between PIN-PMN-PT and Mn-doped PIN-PMN-PT in terms of Domain switching and Polarization Fatigue [27]. Domain evolution under stress is not to be understood by a static linear matrix [28] because of the real-time observation. Experimentally it is observed that the coercive field is dependent on frequency and temperature [29]. While these studies support conservative margins for poling and preload they do not so far provide evidence of hydrophone calibration. Device papers must measure pre-, during- and post-environmental cycling domain-sensitive impedance and receiving response.

C. COMPOSITE CONNECTIVITY AND STRUCTURAL PROCESSING

The incorporation of crystal pillars or plates in polymer reduces the acoustic impedance, allows for curved or large apertures and eliminates lateral modes. Two composites are produced: 2-2 composite is formed by alternating crystal and polymer plates and 1-3 composite is composed of isolated crystal pillars throughout the thickness. The large area dice-and-insert approach in [9] and the curved dice-and-insert in [10] attempt to mitigate fragility and size constraints of direct dicing. The concept is extended towards shaping the acoustic apertures in conformal large-area construction in [16]. A stacked 2-2 tube [17] is used to increase the useful response by using the geometry and the use of multiple elements. This was clearly the case with the latest dual-connectivity layouts, which feature intentional mixing of pillar families, or charge paths. As reported in [20] the (1A,1B)-3 composite is more sensitive and has a wider response than a classical 1-3 comparator. As reported in [21] the design of (1-0)-3 dual-piezo-charge has a large hydrostatic figure of merit and underwater sensitivity gain. These are good, fabricated concepts although, to be ready for deep sea, they require polymer creep, uniformity of kerf, electrode routing, concentration of hydrostatic stress, and water sealing. If there are big room tension gains they should repeat themselves on specimens and after extended tension dwell.

D. ACOUSTIC SENSOR ARCHITECTURES

Scalar hydrophones are pressure measuring devices. In [5] a combined analytical, finite element and tank evidence approach was used in designing the [011]-poled 2-2 thickness-mode configuration near 220 kHz. The 2026 "face-plated" 2-2 study [8] was a study specifically examining the behavior of a hydrophone in the deep sea and comparing the behavior of PMN-PT with Mn:PIN-PMN-PT under uniaxial stress. Examples of low-frequency alternatives are a stacked 2-2 tube [17] and multiple relaxor-crystal disks driving a bender disk [18]. There are different compromises between sensitivity, size, modal purity, pressure load and bandwidth in each architecture. Vector sensors measure the motion of the particles or the pressure gradient and provide the direction. The thickness-shear crystal accelerometers [2] and PIN-PMN-PT cantilever accelerometers [3] are manufactured and experimented

in water. Structural optimization based on prototype is adopted in the compressive PMN-28PT vector sensor in [7]. The conventional piezoceramic triaxial vector hydrophone [4] has been preserved only as a hydrophone system benchmark; the hydrophone's packaging, channel calibration and directionality testing are presented to demonstrate what would be required for a replacement using a single crystal. Volume, frequency, electronics, flow-noise exposure and cross-axis criteria must all be the same.

E. MULTI-RESONANT TRANSDUCER DESIGN

Packaging is part of the transducer. Acoustic loading by matching layers and backing; strain amplification by shells, flextensional frames and benders; potting and cable penetrations for parasitic modes and leakage control. Tian et al. demonstrate advantages of PMN-PT in a sandwich dipole and a matching-layer (ML) transducer [1]. A single-crystal piezotransmitter with high elongation has multi-functionality, both acoustic and electronically, to expand the working band [11]. Two papers, [13] and [14] analyzed broadband flextensional designs using Mn:PIN-PNM-PT. The high field composites characterization [12] and the constants determined at different temperatures to provide Tonpilz design [15] are transmitter oriented but indicate changes in the material and package pertinent for the dual use receiver. An electrical PZN-PT matching-network study reported recently expands the electrical response range but is not alone a measure of reduced acoustic noise and pressure stability. Passive acoustic bandwidth should be separated from any gain caused by a transformer, matching network or amplifier and receiver papers should report input referred noise over the same band.

F.OPERATIONAL QUALIFICATION AND FIELD DEPLOYMENT

The strongest pressure evidence in the set is uneven. A single crystal relaxor transducer was fabricated, tank tested and exposed to 50 MPa [6] but the major reported acoustic response is transmitting response. The face-plated deep-sea hydrophone analysis [8] is not a comprehensive sea trial, but rather a comparison of hydrophone face-plated-crystal choices based on measured stress-dependent material behavior and finite element predictions. The self-powered PIN-PMN-PT beacon was also developed including receiving and transmitting comparisons and experimental sea trials [22; an energy harvesting is also introduced as an innovation here. For each of the primary studies, Table 3 shows its strongest evidence. The significance of the pattern is the following: there are of course material stability studies which explain the mechanism, tank prototypes which demonstrate the acoustic function, and chamber studies which elaborate environmental response, but very few papers illustrate all four. For a passive calibrated hydrophone, near-instability transduction can lead to high history dependence and needs to be tested at low signal levels to produce a large broadband projector gain [30].

G. CROSS-LAYER DESIGN RULES

There are three conditional choices for which the evidence is between one and two. The PMN-PT 2-2 or 1-3 composite is appealing for shallow, broadband small-signal scalar sensing where high small-signal response is important, but the package stress is not large [5], [9], [10], [16]. For larger temperature ranges or higher pressures, Mn:PIN-PMN-PT exhibits a wider domain margin, despite having a decreased peak compliance [8], [15], [25], [27-29]. Shear or compressive vector (DF) architectures [2, 3, 7] are more straightforward for direction finding than compel directionality from a scalar resonator. Dual-connectivity composites [20, 21] would be good candidates when bandwidth and hydrostatic charge need to increase simultaneously but do have a requirement for long dwell times for qualification of both the polymer and the electrode networks. Thus, architecture should be picked from the necessary envelope of environment backwards.

Define frequency band, pressure, temperature, maximum calibration error, self-noise, aperture and number of channels. Next, select the mechanical mode and package; then compute the effective voltage figure of merit under constraint; then choose a crystal composition which has a high enough coercive and phase transition margin. Final design to be compared to ceramic control of same geometry and electronics. The reason that no one paper has all of the application verticals is given by this rule: [22] has the best integrated field evidence, [8] has the best deep-sea receivers, [20] and [21] have the best recent composite performance, and [27] – [29] gives the best stability explanations.

TABLE 3. Evidence matrix

Ref./year	Material or structure	Receiver relevance	Strongest reported evidence	Readiness judgment
[1], 2021	PMN-PT; dipole and matched transducers	Material-to-underwater device comparison	Fabricated acoustic devices; transmit and receive results	Tank-valid application evidence
[2], 2018	Thickness-shear single-crystal accelerometer	Vector hydrophone	Optimized, fabricated, underwater directional test	Realistic tank prototype
[3], 2020	PIN-PMN-PT cantilever accelerometers	Miniature vector sensor	Fabricated sensor and underwater calibration	Realistic tank prototype

[4], 2022	Conventional triaxial piezoelectric vector hydrophone	Architecture benchmark only	Fabricated and underwater tested	System comparator; not crystal evidence
[5], 2023	[011] PIN-PMN-PT/epoxy 2-2	Thickness-mode hydrophone	Theory, FEA, fabrication, calibrated tank response	Realistic tank prototype
[6], 2023	Relaxor single-crystal transducer	Pressure behavior relevant to dual-use receiver	Fabricated; tank and 50 MPa tests; mainly transmit response	Environmental but indirect receiver evidence
[7], 2019	PMN-28PT compressive elements	Vector sensor	FEA optimization and fabricated prototype	Prototype; limited environmental evidence
[8], 2026	Face-plated 2-2; PMN-PT and Mn:PIN-PMN-PT	Deep-sea hydrophone	Stress-dependent data plus FEA receiving prediction	Directly relevant; chamber/sea validation pending
[9], 2021	Large-area 1-3 composite; 3D-print-assisted	Hydrophone active panel	Fabricated 50 mm-scale composite and material tests	Scalable component evidence
[10], 2022	Curved single-crystal composite	Conformal underwater transducer	Fabricated curved composite and properties	Scalable component evidence
[11], 2022	Single-crystal piezocomposite	Extended usable band	Fabricated underwater transducer; mainly transmit/power evidence	Prototype; receiver noise unverified
[12], 2023	PIN-PMN-PT/epoxy 1-3	High-field material margin	Measured high-field composite properties	Component evidence; receiver indirect
[13], 2018	Mn:PIN-PMN-PT class-IV flextensional	Low-frequency reciprocal structure	Model and experimental transducer analysis	Prototype-oriented; receive evidence limited
[14], 2022	Mn:PIN-PMN-PT class-VII flextensional	Broadband reciprocal structure	Design analysis and prototype response	Prototype-oriented; primarily transmit
[15], 2025	[011] Mn:PIN-PMN-PT; Tonpilz	Thermal stability for dual-use receiver	Temperature-dependent full constants plus device model/test	Strong thermal mechanism; receiver indirect
[16], 2023	Conformal large-area single-crystal composite	Shaped acoustic aperture	Fabricated composite and electromechanical tests	Manufacturing evidence
[17], 2017	Stacked 2-2 composite tube	Wideband underwater transducer	Fabricated tube and acoustic characterization	Prototype; qualification absent
[18], 2024	Multiple relaxor-crystal bender disks	Low-frequency transduction	Modeled, fabricated, and tank tested	Realistic geometry; mostly transmit
[19], 2025	Face-shear relaxor single crystal	Compact low-frequency transducer	Optimization and experimental prototype	Prototype; receiver qualification absent
[20], 2025	Dual-pillar (1A,1B)-3 composite	Sensitive broadband receiver	Fabricated; receive and transmit comparison	Strong tank/component evidence
[21], 2026	Dual-piezo-charge (1-0)-3 composite	Underwater acoustic sensing	Fabricated; underwater sensitivity and bandwidth	Strong tank evidence; deep-sea cycling pending
[22], 2025	PIN-PMN-PT transducer plus energy harvester	Self-powered underwater beacon	Receive/transmit comparison and sea trials	Strongest integrated field evidence
[23], 2026	PZN-PT transducer with electrical matching	Broadband electrical response	Circuit analysis and underwater prototype test	Implementable network; noise/pressure pending
[24], 2020	PMN-PT and PIN-PMN-PT boules	Scalable active material	Continuous-feeding Bridgman growth and characterization	Manufacturing-enabling material evidence
[25], 2022	Mn:PIN-PMN-PT boule	Stable low-loss active material	Growth and property characterization	Manufacturing-enabling material

				evidence
[26], 2022	Nd-doped PMN-PT	Ultrahigh piezoelectric active material	Bridgman growth and electrical properties	Material evidence; device stability unknown
[27], 2019	PIN-PMN-PT and Mn-doped crystal	Fatigue and domain retention	Experimental switching and polarization fatigue	Strong mechanism evidence
[28], 2019	[011] PIN-PMN-PT	Package-stress sensitivity	Real-time stress-induced domain observation	Strong mechanism evidence
[29], 2022	PIN-PMN-PT	Temperature/frequency depoling margin	Experimental coercive-field mapping	Strong mechanism evidence

IV. EVALUATION METHODS AND EVIDENCE QUALITY

A. COMPARABLE EVALUATION METRICS

Table 4 provides the minimum values for study of a receiver. The following values should be reported in conjunction: voltage sensitivity, noise-equivalent pressure, bandwidth, directivity, cross-axis rejection and environmental retention. Changes can be explained by Impedance, Capacitance, Dielectric loss, Package resonance. Each curve should be accompanied with its dimensions, crystal volume fraction, crystal cut, crystal poling field, the preload, the water temperature, depth or chamber pressure, the reference hydrophone and the amplifier gain, and the uncertainty.

To record performance, an absolute performance to matched baseline should be used. A ceramic comparison can be made only with the condition that aperture, mode, mechanical frame and the electronics are the same and the test condition remains unchanged. Equal crystal fraction and similar bandwidth definition is also necessary for a composite comparison. Volume and reach are important as one ultra product won't substantiate the numbers that the manufacturer is reporting.

TABLE 4. Minimum metrics for comparable underwater receiver evaluation.

Metric	Required report	Why it matters
Receiving sensitivity	Absolute dB reference, frequency, pressure, temperature, gain removal	Separates the passive receiver from electronics and resonance peaks
Self-noise / NEP	Voltage-noise spectrum, transfer function, amplifier and cable conditions	Sets minimum detectable pressure; exposes dielectric and package noise
Bandwidth	Lower/upper limits, tolerance, response type, center definition	Prevents transmit, conductance, and receive bands from being mixed
Directionality	Beam pattern, cross-axis rejection, channel phase and amplitude match	Required for vector sensing and array calibration
Environmental retention	Pressure-temperature-bias history, dwell, cycling, hysteresis, recovery	Tests calibration rather than simple survival
Manufacturability	Sample count, boule location, geometry tolerance, yield, failures	Shows whether the reported response can be reproduced
Mechanism	Impedance, capacitance, loss, domain or phase diagnostics	Separates crystal change from package or electronics change

B. EVIDENCE QUALITY AND IMPLEMENTATION MATURITY

An implementation test is provided here for the evidence levels through Table 5. Material coupons and simulations can help with screening, but not to show sealing failure, or cable move, amplifier noise, tank reflections, or calibration drift. The fabricated impedance spectrum has nothing to do with underwater receiving, rather only confirming assembly. First direct evidence of a receiver are calibrated tank tests. Requires pressure & temperature chambers, long dwell, cycling and recovery. Sea trials are only strong if the environmental history and reference calibration is documented. There are several realistic laboratory prototype devices in the literature: the vector sensors [2, 3, 7]; thickness-mode hydrophone [5]; large- and curved-composites [9, 10]; and sea-tested beacon [22]. There is important pressure or temperature evidence provided by the studies [6], [8] and [15]. This is by contrast to a finite-element optimization, without a fabricated receiver or a transmitter-only result with an alleged reception quality evaluation. Readiness is set conservatively in Table 3.

TABLE 5. Evidence ladder used to separate implementation evidence from simulation.

Level	Evidence	What it establishes	What it cannot establish
0	Material constants or analytical concept	Potential coefficient and mode	Packaged acoustic performance
1	FEA/equivalent circuit only	Geometric trend and modal feasibility	Fabrication, noise, sealing, or

			calibration
2	Fabricated specimen; air/impedance test	Buildability and electromechanical resonance	Calibrated underwater receiving
3	Calibrated water-tank receiver test	Sensitivity, band, and directivity in controlled water	Deep-sea drift and long aging
4	Pressure/thermal/bias chamber with cycling	Environmental retention and hysteresis	Integration under field handling and ambient noise
5	Documented lake or sea trial	Integrated operation in a real environment	General lifetime unless duration and calibration are sufficient

C. PROPOSED REPRODUCIBLE QUALIFICATION PROTOCOL

A common protocol should begin with at least five devices from more than one boule location. Baseline tests: Impedance, Dielectric Loss, Receiving Sensitivity, Noise Spectrum, Directivity, Cross-axis Response over temperature are measured. Then, the devices will be subjected to stepped hydrostatic loading to a target pressure with defined rates of ascent and descent, dwell at target pressure, thermal cycling and recovery. Acoustic calibration and acoustic impedance are done in situ at low level. Dual use devices introduce controlled bias or transmit pulses below a stated domain margin. The results should consist of the raw curvy and the normalized curvy, uncertainty, the number of failed specimens, hysteresis and the sensitivity after recovery. Material drift and package stress can be distinguished due to a ceramic control and an unpackaged crystal or composite witness. The accelerated aging environment does not really accelerated aging; rather, pressure and temperature are affected together. Last but not least, a protected lake/sea trial should re-record some reference tones and ambient-noise measurements before and after deployment. This sequence directly challenges the innovative challenge – not assuming pressure survival means calibrated sensing.

V. CRITICAL ANALYSIS

It is proposed and acoustically tested the structures of the single-crystal vector sensors [2, 3, 7] and the 2-2 hydrophone [5] which are realistic in terms of their implementations in the laboratory. Manufacturing evidence is also found for large-area and curved dice-and-insert composites [9], [10], [16] yet investment in yield, sealing, and long pressure dwell are not reported. The highest evidence for the self-powered beacon is sea trials and receiving gains measured in ocean trials [22]. It remains to be a substitute for a comprehensive calibration study in the deep sea. Care has to be paid to pressure and temperature papers. The fabricated transducer and pressure exposure are demonstrated in the 50 MPa study [6] but the main acoustic evidence in this case is the transmitting response. The pressure conclusion is a mix of finite element (first)and measured material behavior, while the face-plated 2-2 work [8] is relevant to deep sea receiving. The temperature dependent constants in [15] confirm the Tonpilz design models, but they do not indicate upon hydrophone self-noise and long-term calibration. These are NOT full receiver qualifications, but implementation-enabling methods.

The hydrostatic figures of merit (or underwater sensitivity or bandwidth gains) of composite innovations [20] and [21] are impressive. These are reasonable prototypes that require a polymer creep test, a specimen variation test, an electrode reliability test and a test of combined pressure-temperature history before they could be deployed. Flextensional, bender, face-shear, and electrical-matching studies [13,14,18,19,23] are primarily design or prototype demonstrations and do not necessarily imply a widened transmitting or electrical band which does not indicate broadband low-noise reception. Material-wise growth and domain studies [24-29] are experimental and very strong at coupon scale. They are helpful in explaining their causal value for composition uniformity, doping, fatigue, stress-induced switching, coercive-field variation. These cannot predict packaged sensitivity alone. Near-instability transduction [30] is very effective for broadband projectors but could be hazardous for calibrated passive receivers since history dependence increases near switching. Thus, the most implementable path is the one of composite architecture with Mn:PIN-PMN-PT, conservative preload, and explicit environmental calibration, validated through a tank experiment. Optimizations and receiver claims not based on actual measurement but on reciprocity should continue to be simulation-based.

VII. OPEN CHALLENGES AND FUTURE DIRECTIONS

First open problem is how to distinguish between reversible (package loading) and irreversible (domain change) events occurring in the package under combined pressure, temperature and bias stress. The in-situ impedance, acoustic calibration, and post cycle domain imaging should be performed in

conjunction with each other. Second, self-noise must be regarded at least one level equal to its ability to capture faint signals. Dielectric loss, cable motion and amplifier contribution should be reported in future work in addition to reporting voltage-noise spectra and noise-equivalent pressure. Thirdly, statistics for manufacturing composites are necessary. Studies need to be done to include a variety of positions of the boule, a variety of kerf widths, polymer batches, electrodes and bonds and publish both yield and uncertainty. Fourth, descent, dwell, thermal-cycle and recovery profiles are necessary for the pressure chambers so that PMN-PT, PIN-PNM-PT, Mn doped crystals and ceramics could be compared.

Fifth, the domain evolution, polymer viscoelasticity, face-plate stress, water ingress, and circuit impedance should not be treated independently but be coupled together in the models. The proposed novel target is a self-monitoring face-plated composite hydrophone which maintains calibrated sensitivity, directivity and noise despite repeated deep-sea cycles. It has been suggested to embed pressure and temperature witnesses to choose a reversible calibration state, though it should not be used to conceal irreversible ageing. Essential data includes open raw datasets, geometry, poling history and failed specimens. Lastly, qualification needs to be advanced from replicated tank testing to pressure-temperature chambers, long duration soak and also protected sea trials with reference tones. This evidence chain would turn great crystal coefficients into reliable underwater sensors.

VIII. CONCLUSION

Relaxor-ferroelectric single crystals offer a promising way to develop smaller, more sensitive and widerband underwater receivers. The current progress areas range from scaled growth to engineered domains, shaped composites, vector sensors, pressure aware face plates and autonomous sea-tested systems. But published evidence is scattered among coupons of materials, finite element designs, tank prototypes, and transmitters. Some elements of this survey include a bounded receiver-focused scope, a six-part material to deployment taxonomy, common equations and metrics, 29-study based evidence matrices, and a qualification ladder. The main conclusion is that the peak room pressure sensitivity is no longer the factor that is limiting. The (calibrated) sensitivity, directivity and self-noise of the field shall remain unchanged following coupled pressure-temperature-bias-history. The road between the exceptional crystals and the reliable deep sea hydrophones is replicated manufacturing data, in-situ diagnostics, chamber cycling, and protected sea trials.

REFERENCES

[1] F. Tian, Y. Liu, R. Ma, F. Li, Z. Xu, and Y. Yang, "Properties of PMN-PT single crystal piezoelectric material and its application in underwater acoustic transducer," Appl. Acoust., vol. 175, Art. no. 107827, 2021, doi: 10.1016/j.apacoust.2020.107827.

[2] S. Pyo, J. Kim, H. Kim, and Y. Roh, "Development of vector hydrophone using thickness-shear mode piezoelectric single crystal accelerometer," Sens. Actuators A Phys., vol. 283, pp. 220-227, 2018, doi: 10.1016/j.sna.2018.09.066.

[3] Y. Cho, Y. Je, and W. B. Jeong, "A miniaturized acoustic vector sensor with PIN-PMN-PT single crystal cantilever beam accelerometers," Acta Acust., vol. 4, no. 5, Art. no. 17, 2020, doi: 10.1051/aacus/2020017.

[4] T. Roh, H. G. Yeo, C. Joh, Y. Roh, K. Kim, H. S. Seo, et al., "Fabrication and Underwater Testing of a Vector Hydrophone Comprising a Triaxial Piezoelectric Accelerometer and Spherical Hydrophone," Sensors, vol. 22, no. 24, Art. no. 9796, 2022, doi: 10.3390/s22249796.

[5] Y. Je, M. Sim, Y. Cho, S. G. Lee, and H. S. Seo, "Theoretical and Experimental Studies on Sensitivity and Bandwidth of Thickness-Mode Driving Hydrophone Utilizing A 2-2 Piezoelectric Single Crystal Composite," Sensors, vol. 23, no. 7, Art. no. 3445, 2023, doi: 10.3390/s23073445.

[6] Q. Shi, Z. He, H. Xu, C. Lin, and S. Zhang, "Performance of relaxor ferroelectric single crystal transducer under high hydrostatic pressure," Sens. Actuators A Phys., vol. 360, Art. no. 114523, 2023, doi: 10.1016/j.sna.2023.114523.

[7] H. G. Yeo, J. Choi, C. Jin, S. Pyo, Y. Roh, and H. Choi, "The Design and Optimization of a Compressive-Type Vector Sensor Utilizing a PMN-28PT Piezoelectric Single-Crystal," Sensors, vol. 19, no. 23, Art. no. 5155, 2019, doi: 10.3390/s19235155.

[8] X. Yin, W. Lu, C. Wang, and W. Cao, "Investigation of single-crystal face-plated 2-2 piezocomposites for deep-sea hydrophone applications," J. Acoust. Soc. Am., vol. 159, no. 3, pp. 1963-1972, 2026, doi: 10.1121/10.0042848.

[9] T. Wang, X. Zhao, H. Du, S. Xia, G. Li, H. Guo, et al., "Large-Area Piezoelectric Single Crystal Composites via 3-D-Printing-Assisted Dice-and-Insert Technology for Hydrophone Applications," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 68, no. 10, pp. 3241-3248, 2021, doi: 10.1109/tuffc.2021.3085842.

[10] N. Jia, T. Wang, J. Duan, K. Qiang, S. Xia, H. Du, et al., "High-Performance Curved Piezoelectric Single-Crystal Composites via 3D-Printing-Assisted Dice and Insert Technology for Underwater Acoustic Transducer Applications," ACS Appl. Mater. Interfaces, vol. 14, no. 6, pp. 8137-8145, 2022, doi: 10.1021/acsami.1c21010.

[11] E. Sagaas Røed, M. Bring, M. Frijlink, A. Henriksen, F. Tichy, E. M. Åsjord, et al., "Underwater single crystal piezocomposite transducer with extended usable frequency band," Ultrasonics, vol. 125, Art. no. 106794, 2022, doi: 10.1016/j.ultras.2022.106794.

[12] H. Zhao, Z. Chen, G. Zheng, C. Wang, and W. Cao, "Characterization of high-field properties of 0.28PIN-0.42PMN-0.30PT single crystal/epoxy 1-3 composite for acoustic transducer applications," Appl. Acoust., vol. 214, Art. no. 109704, 2023, doi: 10.1016/j.apacoust.2023.109704.

[13] R. Guo, S. Li, D. An, T. Han, J. Chen, and W. Cao, "Comprehensive analysis of Mn:PIN-PMN-PT single crystals for Class IV flextensional transducer," Ceram. Int., vol. 44, no. 3, pp. 2864-2868, 2018, doi: 10.1016/j.ceramint.2017.11.033.

[14] J. Zheng, S. Li, and B. Wang, "Design and analysis of a broadband class VII flextensional transducer with the third-generation crystal, Mn:PIN-PMN-PT," Sens. Actuators A Phys., vol. 345, Art. no. 113777, 2022, doi: 10.1016/j.sna.2022.113777.

[15] B. Kwon, S. Pyo, J. Eo, H. S. Seo, and Y. Roh, "Temperature dependence of the full material constants of [011]-poled Mn-doped 0.32PIN-0.39PMN-0.29PT single crystals, and its effect on the performance of an underwater Tonpilz transducer," Sens. Actuators A Phys., vol. 390, Art. no. 116602, 2025, doi: 10.1016/j.sna.2025.116602.

[16] N. Jia, T. Wang, L. Ning, Z. Ma, Y. Dang, C. C. Li, et al., "Conformally Large-Area Single-Crystal Piezocomposites with High Performance for Acoustic Transducers," ACS Appl. Mater. Interfaces, vol. 15, no. 30, pp. 36611-36619, 2023, doi: 10.1021/acsami.3c07673.

[17] W. Hong-wei and W. Li-kun, "Wide band underwater acoustic transducer for stacked 2-2 piezoelectric composite material tube," Ferroelectrics, vol. 520, no. 1, pp. 10-21, 2017, doi: 10.1080/00150193.2017.1328727.

[18] Q. Shi, Z. He, H. Xu, C. Lin, and S. Zhang, "Research on low-frequency bender disk transducer driven by multiple relaxor ferroelectric single crystal disks," Appl. Acoust., vol. 216, Art. no. 109808, 2024, doi: 10.1016/j.apacoust.2023.109808.

[19] S. Wu, Y. Xie, F. Bai, and D. Teng, "Optimal design and experimental study on a novel relaxor ferroelectric single crystal transducer based on face shear vibration mode," Ultrasonics, vol. 156, Art. no. 107763, 2025, doi: 10.1016/j.ultras.2025.107763.

[20] Y. Lei, Z. Gao, G. Gan, W. Bai, Y. Wei, B. Wang, et al., "A High-Sensitivity, Broadband (1A,1B)-3 Single-Crystal Composite Ultrasonic Transducer," Adv. Funct. Mater., vol. 35, no. 11, Art. no. 2417084, 2025, doi: 10.1002/adfm.202417084.

[21] Y. Lei, X. Li, Z. Hou, B. Wang, S. Zheng, Y. Wei, et al., "Dual-Piezo-Charge Strategy in (1-0)-3 Single-Crystal Composite for Enhancing Underwater Acoustic Sensing," Nano-Micro Lett., vol. 18, no. 1, Art. no. 259, 2026, doi: 10.1007/s40820-026-02102-1.

[22] S. Gao, J. Zhou, X. Gao, R. Liu, H. Jiang, J. Chang, et al., "Self-Powered Underwater Acoustic Beacon System Enabled by Dual Bluff Body Energy Harvester with Relaxor Ferroelectric Crystals," Adv. Mater. Technol., vol. 10, no. 22, Art. no. e00982, 2025, doi: 10.1002/admt.202500982.

[23] Y. Jia, H. Shi, J. Zhang, L. Zang, Z. Mao, and S. Zhang, "Broadband Electrical Matching Network for PZN-PT Single Crystal Underwater Acoustic Transducer," IEEE Sens. J., vol. 26, no. 5, pp. 6614-6624, 2026, doi: 10.1109/jsen.2026.3650828.

[24] K. Echizenya, K. Nakamura, and K. Mizuno, "PMN-PT and PIN-PMN-PT single crystals grown by continuous-feeding Bridgman method," J. Cryst. Growth, vol. 531, Art. no. 125364, 2020, doi: 10.1016/j.jcrysgro.2019.125364.

[25] K. Echizenya, N. Noda, and H. Noro, "Characterization of Mn-Doped PIN-PMN-PT Single Crystal Grown by Continuous-Feeding Bridgman Method," Crystals, vol. 12, no. 9, Art. no. 1183, 2022, doi: 10.3390/cryst12091183.

[26] Z. Chen, T. Deng, R. Chen, D. Lin, W. Di, H. Chen, et al., "Bridgman growth and electrical properties of Nd-doped PMN-PT single crystal with ultrahigh piezoelectricity," CrystEngComm, vol. 24, no. 4, pp. 837-845, 2022, doi: 10.1039/d1ce01116b.

[27] Y. Zhou, Q. Li, F. Zhuo, C. Xu, Q. Yan, Y. Zhang, et al., "Domain switching and polarization fatigue in rhombohedral PIN-PMN-PT and Mn-doped PIN-PMN-PT single crystals," J. Am. Ceram. Soc., vol. 102, no. 11, pp. 6668-6679, 2019, doi: 10.1111/jace.16461.

[28] Y. Liu, J. Xia, P. Finkel, S. D. Moss, X. Liao, and J. M. Cairney, "Real-time observation of stress-induced domain evolution in a [011] PIN-PMN-PT relaxor ferroelectric single crystal," Acta Mater., vol. 175, pp. 436-444, 2019, doi: 10.1016/j.actamat.2019.06.023.

[29] L. Cui, Z. Chen, Y. Lü, and W. Cao, "Dependence of coercive field of PIN-PMN-PT single crystal on temperature and frequency," J. Appl. Phys., vol. 131, no. 12, Art. no. 124102, 2022, doi: 10.1063/5.0079332.

[30] P. Finkel, C. Lynch, and A. Amin, "Transduction modality near instability in domain engineered relaxor ferroelectric single crystals," Smart Mater. Struct., vol. 33, no. 1, Art. no. 013001, 2024, doi: 10.1088/1361-665x/ad06de.

© 2026 Scholarly Horizon Publication. All rights are reserved.