

Design of a Layered FeGaB/ZnO Magnetoelectric Composite Antenna



Wu-sheng Ji¹, Boyuan Luo^{1,*}, Cao Huang², Junzhe Lu¹, Jie Gao¹, Leilei Wang¹

¹School of Electronic Engineering, Tianjin University of Technology and Education, Tianjin 300222, China

²School of Engineering, Xizang Minzu University, Xianyang 712082, China

Abstract: The Layered magnetoelectric composite antennas, formed by combining magnetostrictive and piezoelectric materials, have emerged as a design paradigm for bulk acoustic wave (BAW) magnetoelectric antennas. This paper proposes a design scheme for a layered magnetoelectric antenna based on FeGaB magnetostrictive material and ZnO piezoelectric material. This design aims to leverage the excellent magnetostrictive properties of FeGaB and the favorable piezoelectric characteristics of ZnO to reduce transmission energy loss through effective coupling at the interlayer interfaces, thereby achieving efficient energy transmission and signal reception in the low-frequency band. Experimental simulations were conducted using COMSOL software, the results indicate that, compared to traditional single-component piezoelectric antennas, the FeGaB/ZnO magnetoelectric composite antenna exhibits smaller dimensions within the low-frequency operating range below 1 GHz. This effectively reduces the overall volume of the antenna, meeting the application requirements of miniaturized, low-power wireless communication devices. This design approach provides valuable insights for the development of miniaturized antennas in the low-frequency band. abstract should be a concise single paragraph, ranging from 200 to 400 words, and should not include any reference citations or footnotes. For research articles, it should provide a brief overview of the background, objective, method, result and conclusion of your article before the main body. In case report, abstract should include background, case presentation and conclusion. It is important to ensure that the abstract presents an objective representation of the article, avoiding the inclusion of results that are not substantiated in the main text and refraining from exaggerating the main conclusions.

Keywords: Magnetoelectric Composite Antennas; Piezoelectric Antennas; Acoustic Coupling; Layered Structures; FeGaB/ZnO

DOI: [10.57237/j.se.2026.03.002](https://doi.org/10.57237/j.se.2026.03.002)

1 Introduction

With advances in technology and the growing demand for communication in certain scenarios, traditional electromagnetic antennas face challenges such as large size and low radiation efficiency when operating at low frequencies, making it difficult to meet the development needs of portable and miniaturized communication devices. Consequently, the development of compact, high-performance low-frequency antennas has become one of

the current research hotspots in the field of antenna technology. Acoustic-wave antennas offer a novel method of generating electromagnetic waves. Their operating principle is based on “multi-physics coupling effects between magnetic, acoustic, and electric fields” rather than traditional electromagnetic resonance. Through a composite structure consisting of piezoelectric and magnetostrictive layers, electromagnetic and acoustic

Funding: Key Project of Natural Science Foundation of Xizang Autonomous Region (Grant No. XZ202601ZR0046).

*Corresponding author: Boyuan Luo, 1843078886@qq.com

Received: 22 July 2026; Accepted: 7 September 2026; Published Online: 8 October 2026

<http://www.sciandeng.com>

energy can be converted into one another [1]. This breakthrough overcomes the fundamental limitations of power-supply-based antennas. The 2-2-type layered magnetoelectric composite antenna offers the advantages of easy integration and simple processing and design [2].

In 1983, R.F. Milsom crew proposes a sound wave resonator using zinc oxide as the piezoelectric layer, equipped with a silicon substrate and upper and lower electrodes, and demonstrates that performance is optimal when the ratio of the silicon substrate thickness to the total thickness is 0.25 [3]. In 2022, J. R. Li crew suggests that the performance of the magnetostrictive layer in a bulk acoustic wave (BAW) antenna is optimal when it is stacked with the piezoelectric layer at equal thicknesses [4]. Currently, research on layered magnetoelectric composite antennas is limited and focuses primarily on verifying the performance of specific material combinations, lacking systematic studies on the transition from piezoelectric to magnetoelectric structures. FeGaB, as a high-performance magnetostrictive material, possesses a high magnetostrictive coefficient and good mechanical toughness [5], while ZnO piezoelectric material features stable piezoelectric response and excellent compatibility [6]. The layered composite of these two materials is expected to further enhance magnetoelectric coupling efficiency [7]. Based on this, this paper utilizes COMSOL Multiphysics 6.3 software to focus on the design methodology of layered FeGaB-ZnO magnetoelectric antennas, simulating both ZnO piezoelectric antennas and FeGaB/ZnO bulk acoustic wave (BAW) antennas, with experimental results consistent with the expected design. Through theoretical analysis and experimental verification of parameter tuning for each functional layer, this study aims to address key challenges in miniaturized antenna design and provide a feasible technical pathway for their practical application.

2 Antenna Design

2.1 ZnO Piezoelectric Antenna

According to the theoretical model of acoustic excitation antennas using piezoelectric crystals, when an alternating voltage is applied across the two ends of a piezoelectric material to create an alternating electric field, the centers of positive and negative charges within the non-centrosymmetric unit cell of the piezoelectric crystal shift. This causes the unit cell to deform, ultimately resulting in

macroscopic deformation [8].

At the same time, because piezoelectric crystals are dielectrics, there are essentially no free charges within them; the local movement of bound charges causes the unit cell to transform into an electric dipole whose orientation varies with the frequency of the electric field, thereby forming an electric dipole moment and generating a certain degree of electric polarization. When polarization occurs within the crystal, the polarized charges act as a source of electric field, generating a displacement vector and displacement current density, thereby radiating electromagnetic waves outward [9]. Accordingly, by placing electrodes at both ends of the piezoelectric material to create an electric field, we can excite the deformation of the piezoelectric layer and radiate electromagnetic waves outward, ultimately forming a piezoelectric antenna; furthermore, to meet practical engineering requirements, a substrate is added. Based on the layered piezoelectric antenna model, the paper proposes an equation relating the thickness of the piezoelectric resonator to its operating frequency and constituent materials [10]. Using this relationship between the piezoelectric layer thickness and parameters such as material and operating frequency, we can determine the antenna thickness with 433 MHz in the ISM band as the operating frequency. In this paper, ZnO is selected as the material for the piezoelectric layer. Substituting the basic material parameters into the layer thickness formula:

$$f = \frac{1}{2h} \sqrt{\frac{E}{\rho}} \quad (1)$$

Here, f is the operating frequency, h is the thickness of the piezoelectric layer, E is the Young's modulus, ρ is the density of the piezoelectric material.

The thickness of the piezoelectric layer is determined to be 6.9 μm . Aluminum electrode layers are then added above and below the piezoelectric layer to supply power to it. To minimize the impact of the electrode layers on the antenna, their thickness must be significantly smaller than that of the piezoelectric layer; in this experiment, a thickness approximately 10 times smaller is selected, resulting in an electrode thickness of 0.1 μm for both the top and bottom layers. Based on the optimal thickness ratio formula for ZnO piezoelectric antennas with a silicon substrate, the silicon substrate thickness is determined to be 2.3 μm . However, since the silicon substrate is a rigid, heavy load that will further lower the overall resonant frequency of the

piezoelectric antenna and this cannot be simply corrected using the equivalent thickness formula. Further refinement is required based on feedback from simulation experiments [11]. In this experiment, we approached the target frequency band by incrementally reducing the piezoelectric layer thickness derived from the thickness formula by 0.1micron each time, recalculating the substrate thickness based on the new piezoelectric layer thickness, until the antenna's main mode frequency fell within the target band. The piezoelectric antenna has a length of 200 μm . From top to bottom, it consists of a 0.1 μm Al top electrode, a 6 μm ZnO piezoelectric layer, a 0.1 μm Al bottom electrode, and a 2 μm silicon substrate. The ZnO piezoelectric antenna model is shown in Figure 1.



Figure 1 Model of ZnO piezoelectric antenna

2.2 Layered FeGaB/ZnO Magnetoelectric Composite Antenna

For the FeGaB/ZnO composite antenna section, a ZnO piezoelectric antenna is used as the base, with a magnetostrictive layer placed on top of it. FeGaB was

selected as the material for the magnetostrictive layer. The layers were stacked using the optimal configuration with a 1:1 thickness ratio between the piezoelectric and magnetostrictive layers [12]. In two-dimensional simulations, since the materials are in very close contact, interfacial coupling effects must also be taken into account. According to the sound intensity reflection coefficient formula in the field of acoustics [13]:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 \quad (2)$$

Here, Z_1 and Z_2 are the acoustic impedances of the two media.

Calculate the acoustic impedance using the formula:

$$Z = \rho \times V \quad (3)$$

where ρ is the density of the material and V is the Longitudinal wave velocity.

FeGaB is a composite thin-film material, and its longitudinal wave velocity must be calculated using the following formula [14]:

$$V_{\text{FeGaB}} = \sqrt{\frac{E(1-\nu)}{\rho_2(1+\nu)(1-2\nu)}} \quad (4)$$

Here, ν is the Poisson's ratio of the FeGaB material, E is the Young's modulus of the FeGaB material, and ρ_2 is the density of the FeGaB material.

The material parameters are listed in the table below:

Table 1 Material Properties

Material	Young's modulus (Pa)	Poisson's ratio	Density (kg/m ³)	Longitudinal wave velocity
FeGaB	101×10^9	0.3	7870	--
ZnO	138×10^9	0.33	5680	6000

Calculations yield the acoustic impedance of ZnO as $Z_{\text{ZnO}} = 34,080,000 \text{ Rayl}$. The longitudinal wave velocity of FeGaB is $V_{\text{FeGaB}} \approx 4,156 \text{ m/s}$, and calculations show that its acoustic impedance is $Z_{\text{FeGaB}} = 32,707,720 \text{ Rayl}$. Based on the above formula, the acoustic reflection coefficient is $R \approx 0.000422$, which is approximately 0.0422%. This indicates that the acoustic impedances of the two materials are very close, resulting in minimal acoustic intensity reflection loss at the interface; the vast majority of sound waves can be transmitted, demonstrating excellent interface coupling performance [15]. The FeGaB/ZnO magnetoelectric composite antenna model is shown in Figure 2. From top to bottom, the layers consist of a 6 μm

iron gallium boride (FeGaB) layer, a 0.1 μm Al top electrode, a 6 μm ZnO piezoelectric layer, a 0.1 μm Al bottom electrode, and a 2 μm silicon substrate.

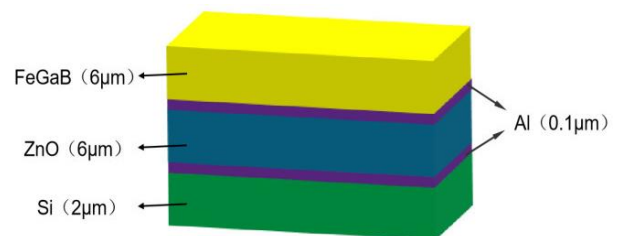


Figure 2 Antenna model of FeGaB/ZnO magnetoelectric composite material

3 Simulation Experiments

When simulating piezoelectric antennas using COMSOL Multiphysics 6.3, only the electric field needs to be coupled; for acoustic wave antennas, the magnetic field must also be coupled. During the simulation, the appropriate physical properties must be assigned to each material layer. For the piezoelectric layer, the elastic matrix, piezoelectric matrix, and dielectric matrix must be set. For the magnetostrictive layer, key parameters such as the magnetostrictive coefficient, elastic modulus, and magnetic permeability must be defined; these can also be specified when selecting the materials for each layer. Since the layered structure has a small thickness but relatively large lateral dimensions, a fine mesh is used in the thickness direction to accurately capture the reflection and transmission behavior of sound waves at the interfaces, while the mesh size can be appropriately increased in the lateral direction to reduce computational load. For this experiment, rectangular meshes are selected, with the maximum mesh element size not exceeding 1/10 of the minimum wavelength, ensuring simulation accuracy and computational efficiency.

Add frequency-domain and characteristic frequency studies to analyze the mode diagrams, potential and electric field maps, stress distribution maps, and key performance metrics such as Q-factor and S-parameters for the two antennas at different frequencies. In the frequency-domain analysis, a frequency range encompassing the operating frequency is defined, and the admittance plot is examined using large steps to quickly determine the antenna's center operating frequency; this also provides a precise frequency range for the characteristic frequency study, thereby reducing the number of experiments required [16].

4 Experimental Results

4.1 ZnO Piezoelectric Antenna

As shown in Figure 3, which depicts the principal mode diagram of the piezoelectric antenna, the antenna's center operating frequency is 440.8 MHz, consistent with the dashed line admittance curve shown in Figure 4. The absolute value of admittance curve forms a sharp main resonance peak at 440.8 MHz, with a peak admittance of 0.2731 S, corresponding to the main operating mode of the piezoelectric transducer. At this point, the antenna's equivalent impedance is at its lowest and energy coupling efficiency is at its highest, making it the antenna's core

operating frequency. The admittance decays rapidly on both sides of the main peak, accompanied by weak secondary peaks near 444 MHz and 449 MHz and a deep valley at 453 MHz, corresponding to higher-order parasitic piezoelectric modes and anti-resonance points, respectively. The overall curve exhibits typical high-Q piezoelectric resonance characteristics, indicating that this zinc oxide piezoelectric antenna possesses excellent frequency selectivity and a concentrated energy response near 440.8 MHz while the secondary peaks and troughs also reflect the multimodal vibration characteristics of the piezoelectric material, providing a clear reference for subsequent matching network design and spurious mode suppression.

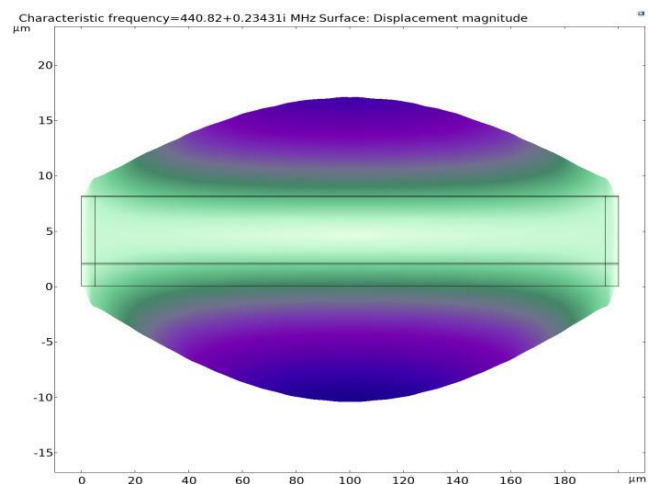


Figure 3 Mode shapes of ZnO piezoelectric antenna

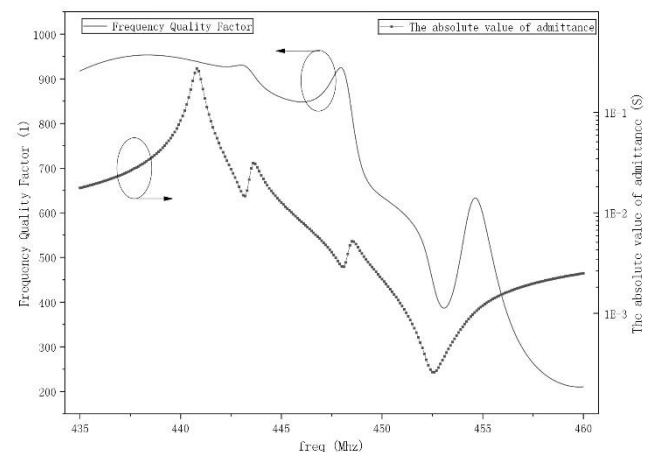


Figure 4 The frequency quality factor and absolute value of admittance of ZnO piezoelectric antenna

The solid line shows the frequency quality factor plot for the piezoelectric antenna; at a frequency of 440.8 MHz, the Q-factor is 938.65.

Figure 5 shows the S-parameter plot of the piezoelectric antenna. The curve clearly reflects the port matching performance of the zinc oxide piezoelectric antenna. A deep trough of -12.387 dB appears at 443.4 MHz, corresponding to the antenna's main operating resonance point. At this point, port reflection power is significantly reduced, and the efficiency of energy transfer to the antenna's vibrating structure is markedly improved. Reflection loss reaches its optimal value at 443.4 MHz. A

shallow valley of approximately -3 dB appears near 448 MHz, corresponding to the parasitic sub-modes of the piezoelectric antenna. After 450 MHz, the S-parameters gradually approach 0 dB, indicating that port reflection significantly increases and matching performance rapidly declines as the frequency deviates from the resonance point. The overall curve exhibits the typical matching characteristics of a narrowband piezoelectric antenna.

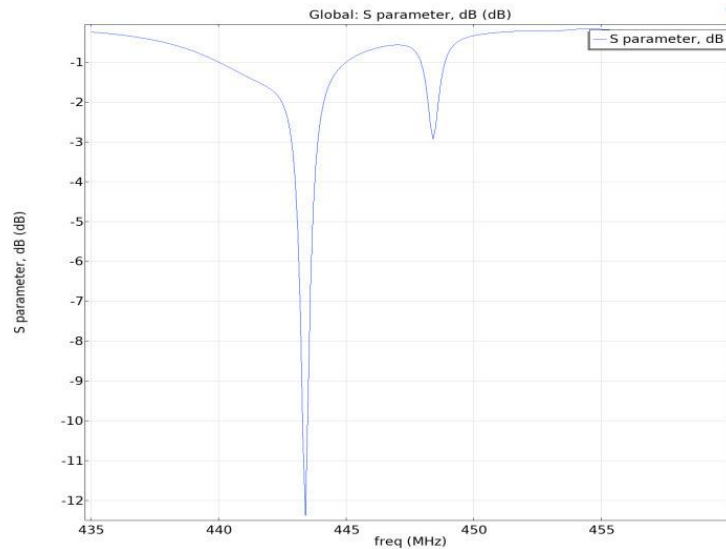


Figure 5 S-parameter curves for ZnO piezoelectric antennas

4.2 FeGaB-ZnO Composite Antenna

Figure 6 shows the principal mode diagram of the composite antenna, with the principal mode occurring at 436.79 MHz.

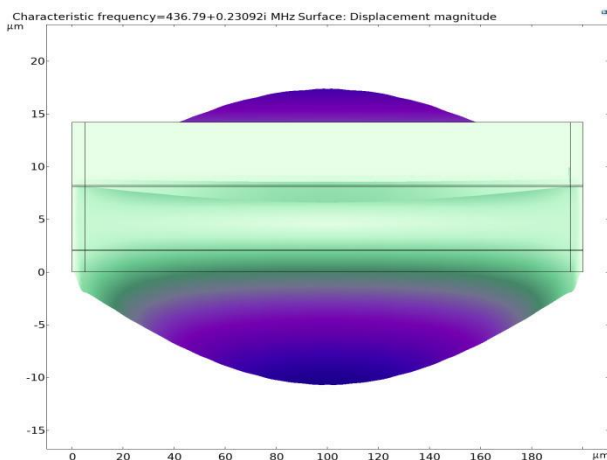


Figure 6 Mode shapes of FeGaB-ZnO composite antenna

The absolute value of admittance which is the dashed

line in figure 7 clearly illustrates the acoustic resonance characteristics of the bulk acoustic wave magnetoelectric antenna; the curve exhibits a multi-peak distribution, with the main peak located at approximately 436.8 MHz, with an admittance of 0.274S. This is the device's main resonance mode; at this frequency, the bulk acoustic waves excited by the zinc oxide piezoelectric layer form standing waves within the structure, resulting in the strongest electromechanical coupling and the highest energy conversion efficiency. The secondary resonance peaks appearing to the right of the main peak are caused by higher-order acoustic modes of the structure, parasitic modes induced by acoustic impedance mismatches between different material layers, or stray resonances resulting from substrate acoustic wave reflection coupling. These reflect the complex propagation and coupling behavior of acoustic waves within the multilayer composite structure, while the overall trend of the curve on the logarithmic axis illustrates the distribution of the device's electromechanical coupling strength and loss at different frequencies. The high admittance near the main peak corresponds to low impedance and strong coupling, while

the admittance in the low- and high-frequency bands far from the resonance peak is significantly reduced, corresponding to weak electromechanical responses in the device's non-resonant state. This result indicates that the antenna exhibits optimal magnetoelectric transduction and operational performance near 436.8 MHz. The operating

frequency band of this FeGaB-ZnO bulk acoustic wave antenna differs little from that of a ZnO piezoelectric antenna, which demonstrates that acoustic wave transmission involves minimal loss and that the two materials, FeGaB and ZnO, exhibit good matching performance.

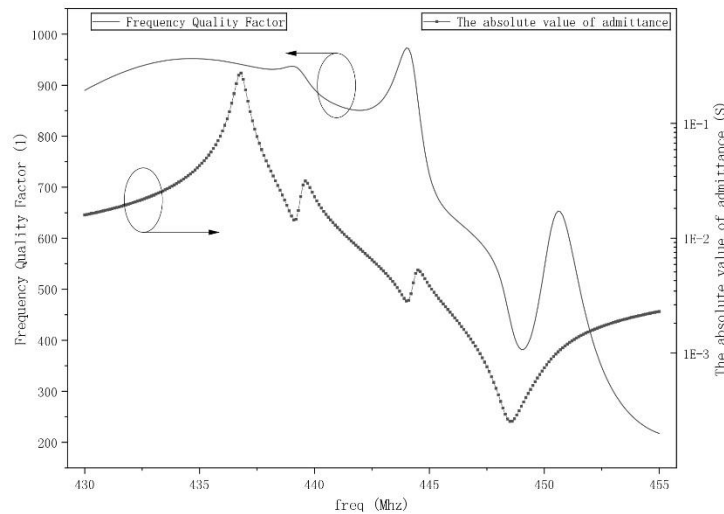


Figure 7 The frequency quality factor and absolute value of admittance of FeGaB-ZnO composite antenna

The solid line in Figure 7 shows that the frequency quality factor of this bulk acoustic wave antenna reaches 940.75 at 436.8 MHz, which is the highest Q-value in the main resonance mode across the entire frequency band, indicating that energy loss is minimal at this frequency point and that resonance stability and signal selectivity are optimal.

As shown in Table 2, the Q-factor of the FeGaB-ZnO

composite antenna is slightly higher than that of the ZnO piezoelectric antenna. At the main mode resonance frequency, the FeGaB-ZnO composite antenna is closer to the expected frequency of 433 MHz. The corresponding peak admittance of the composite antenna is slightly higher, indicating that the composite antenna exhibits lower loss in acoustic wave transmission at the main operating frequency.

Table 2 Comparison of Antenna Performance Parameters

Antenna Type	Master Mold Q-value	Natural frequency of the main mold	Peak admittance of the main mold
ZnO piezoelectric antenna	938.65	440.8 MHz	0.2731S
FeGaB-ZnO Composite Antenna	940.75	436.8 MHz	0.2743S

5 Conclusions

This paper proposes a method for designing FeGaB-ZnO composite antennas using two-dimensional simulations in COMSOL Multiphysics 6.3. The design process begins by determining the primary operating frequency band to establish the thickness of the ZnO piezoelectric antenna, followed by the integration of a suitable FeGaB magnetostrictive layer to form a layered FeGaB-ZnO magnetoelectric antenna. This design scheme combines 2D simulation with experimental debugging to achieve the

precise design of layered magnetoelectric antennas, providing a feasible path for the miniaturization and high-performance development of bulk acoustic wave magnetoelectric antennas. Its excellent chemical stability and electromechanical coupling characteristics offer broad application prospects in fields such as low-power IoT communication, wireless sensor nodes, and portable medical devices. In the future, the thickness ratio of the layered structure can be further optimized, new combinations of magnetostrictive materials can be explored, or temperature compensation mechanisms can be introduced to enhance the antenna's stability and

adaptability in complex environments, thereby advancing the practical engineering applications of magnetoelectric antenna technology.

References

- [1] C. R. Peng, J. R. Li, H. Zhong, et al., Analytical calculation on radiation performance of bulk acoustic wave magnetoelectric antenna. *J. Piezoelectrics & Acoustooptics*. 2020, 42(1), 34-37. <https://doi.org/10.11977/j.issn.1004-2474.2020.01.009>
- [2] R. E. Newnham, D. P. Skinner, L. E. Cross. Connectivity and Piezoelectric-Pyroelectric Composites. *J. Materials Research Bulletin*, 1978, 13(5), 525-536. [https://doi.org/10.1016/0025-5408\(78\)90161-7](https://doi.org/10.1016/0025-5408(78)90161-7)
- [3] R.F. Milsom, J.E., Curran, S.L. Murray, S. Terry-Wood, and M. Redwood, Effect of Mesa Shaping on Spurious Modes in ZnO/Si Bulk-Wave Composite Resonators. *J. Proc. IEEE Ultrason. Symp.* 1983, 498-503. <https://doi.org/10.1109/ULTSYM.1983.198104>
- [4] REN W C, CHEN S, GAO Y, et al. Progress and technical framework of the BAW mediated magnetoelectric antenna. *J. Chinese journal of radio science*, 2021, 36(4): 491-497 + 51(in Chinese). <https://doi.org/10.13443/j.cjors.2020042202>
- [5] Y. Gao, S. Zare, X. Yang, et al. High quality factor integrated gigahertz magnetic transformers with FeGaB/Al₂O₃ multilayer films for radio frequency integrated circuits applications. *J. Journal of Applied Physics*, 2014, 115(17 Pt.3): 17E714-1-17E714-3. <https://doi.org/10.1063/1.4868622>
- [6] Y. Y. Sun, C. J. Shi, S. J. Liu, et al., Preparation of ZnO piezoelectric thin films and analysis of piezoelectric simulation characteristics. *J. Mechanical Research & Application*. 2023, 36(1). <https://doi.org/10.16576/j.ISSN.1007-4414.2023.01.031>
- [7] J. Qi, C. Zhang and Y. Li, "Dual-Band Acoustics Promoted Low Frequency Antenna," 2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI), Denver, CO, USA, 2022, pp. 2036-2037, <https://doi.org/10.1109/AP-S/USNC-URSI47032.2022.9886031>
- [8] FU Yifan, XU Guokai, ZHU Xiangwei, XIAO Shaoqiu, ZHANG Jinghao, ZHONG Jiuping, LI Wanqing, LI Junru, WANG Yuhang, WANG Ziyue, LI Du. Research on Acoustically Excited Miniaturized Antenna Technology Based on Piezoelectric Crystal in Low-Frequency. *J. Journal of Electronics & Information Technology*, 2023, 45, 11. <https://doi.org/10.11999/JEIT230914>
- [9] G. T. Rado, V. J. Folen; Magnetoelectric Effects in Antiferromagnetics. *J. Appl. Phys.* 1 March 1962, 33, 3. <https://doi.org/10.1063/1.1728630>
- [10] Chen, S.; Li, J.; Gao, Y.; Li, J.; Dong, H.; Gu, Z.; Ren, W. A Micromechanical Transmitter with Only One BAW. *J. Magneto-Electric Antenna. Micromachines*. 2022, 13, 272. <https://doi.org/10.3390/mi13020272>
- [11] Novel Gas Sensor Arrays Based on High-Q SAM-Modified Piezotransduced Single-Crystal Silicon Bulk Acoustic Resonators. *J. Sensors*, 2017, 177. <https://doi.org/10.3390/s17071507>
- [12] Dong Hongmei, Guo Huihui, Li Junru, Li Jianbo, Gan Xiuxiu. 2023. An equivalent circuit for magnetoelectric composites operating in a longitudinal mode resonance: BAW-actuated mechanical antenna. *Physica Scripta*. 98. <https://doi.org/10.1088/1402-4896/acce82>
- [13] Cervenka, Milan, Bednarik, Michal. Calculation of an axial temperature distribution using the reflection coefficient of an acoustic wave. *J. The Journal of the Acoustical Society of America*, 2015, 138(4): EL359-EL364. <https://doi.org/10.1121/1.4931830>
- [14] Harrypersad-Daniel, A. M., Blake, O. O., Ramsook, R.. Determining the static Young's modulus and Poisson's ratio, and compressive strength of the friable Erin Formation rocks using P-wave velocity. *J. Journal of Applied Geophysics*, 2022, 198. <https://doi.org/10.1016/j.jappgeo.2022.104557>
- [15] Andrew Dawson, Gideon Gouws, Paul Harris, et al. Acoustic Impedance Matching with Porous Aluminium.C. 2009 IEEE Sensors. [v.1]: IEEE, 2009: 49-52. <https://doi.org/10.1109/ICSENS.2009.5398122>
- [16] Batool M. Saloom, Anwaar A. Al-Dergazly. Designing magnetic field filter based on no-core fiber assisted by a ferrofluid. *J. Applied physics, B. Lasers and optics*, 2025, 131(1): 1.1-1.10. <https://doi.org/10.1007/s00340-024-08379-7>