Design of Low-frequency Laminated Magnetoelectric Composite Antennas

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Abstract: This paper designs a layered magnetoelectric composite antenna with a FeGaB/PZT-5H/FeGaB sandwich-structured configuration. Benefiting from the strong magnetostrictive effect of FeGaB and the superior piezoelectric performance of PZT-5H, this symmetrical sandwich stack is expected to realize efficient magnetoelectric coupling under external excitation. The antenna model is established using the three-dimensional finite element simulation software COMSOL Multiphysics, with a focus on analyzing its resonant frequency, stress distribution, and magnetic flux density characteristics. The vibration mode and magnetoelectric coupling mechanism of the composite structure are further discussed to reveal the internal energy transfer process between magnetic and electric fields. The output voltage response under alternating magnetic field excitation is characterized, which serves as a key indicator to evaluate the magnetoelectric conversion capacity. Simulation results show that the antenna achieves the optimal resonant frequency and energy conversion efficiency at 59.03 kHz, validating its application potential in low-frequency miniaturized radio-frequency devices. Compared with conventional low-frequency antennas relying on winding coils, this magnetoelectric composite scheme can effectively reduce the device size without requiring large matching inductors. In addition, the designed structure maintains relatively simple preparation difficulty, which is conducive to subsequent sample fabrication and experimental verification. It offers a feasible technical route for the development of compact, lightweight low-frequency receiving antennas in underwater communication and near-field detection scenarios.

Keywords: Bulk Acoustic Wave; Magnetoelectric Composite Antenna; Low Frequency; FeGaB; PZT-5H

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1 Introduction

Traditional electrically small antennas often suffer from low radiation efficiency and limited bandwidth under size-constrained conditions, making it difficult to meet the requirements of relevant applications. In this context, magnetoelectric composite antennas utilizing bulk acoustic waves (BAW) and operating on the electro-acoustic-magnetic coupling principle are increasingly emerging as a focal point of antenna research [1]. BAW magnetoelectric antennas leverage an "electrical-acoustic-magnetic-electromagnetic wave" conversion mechanism to shift the size constraint from the electromagnetic wavelength to a much shorter acoustic wavelength, thereby achieving a breakthrough in antenna miniaturization. This type of antenna utilizes the coupling between piezoelectric and magnetostrictive materials to convert electrical signals into magnetic field radiation, achieving relatively high radiation efficiency while maintaining a small size, thus offering clear advantages in miniaturization.

In 2015, Yao and colleagues initially put forward the theory of BAW-mediated magnetoelectric (magnetic-electric, ME) antennas [2]. This study focused primarily on the GHz radio frequency band with a typical operating frequency of approximately 1GHz, and employed a three-dimensional multiscale finite-difference time-domain (FDTD) method to simulate and validate the antenna performance, not only

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theoretically confirming the radiation effectiveness of the antenna but also improving the prediction accuracy of the radiation Q-factor, resonance mode, stress decay, impedance, and radiated power. In 2017, Nan et al. proposed an acoustically driven MEMS magnetoelectric antenna based on a heterostructure [3]. By employing a FeGaB/AlN magnetoelectric heterostructure, a strong magnetoelectric coupling effect is achieved between the two functional thin films; relying on acoustic resonance for electromagnetic wave transmission and reception, the antenna size can be reduced to the order of one-thousandth of the wavelength of conventional electromagnetic resonant antennas while maintaining magnetic field performance, thus achieving a breakthrough in the miniaturization and practical application of conventional antennas. In 2018, Lin et al. conducted further research on BAW antennas [4], proposing an effective method to enhance antenna gain, and systematically analyzed and compared two array configurations: series and parallel. In 2019, Xu et al. constructed a magnetoelectric composite antenna based on PZT fibers and Metglas and investigated the polarization of piezoelectric materials [5], the study found that more complete polarization is more beneficial to antenna radiation. In 2020, Yao et al. simulated a 1.3-μm-thick strain-mediated bulk acoustic-wave (BAW) multiferroic antenna and demonstrated its capabilities [6], concluding that reducing the FMR linewidth is a key feature for achieving higher antenna radiation efficiency. In 2020, Liang et al. developed a Bragg reflective layer-type BAW antenna [7], compared with traditional structures requiring cavity release, this antenna eliminates the cavity fabrication process, effectively reduces residual film stress, optimizes magnetic domain consistency, and enhances the effective magnetization intensity. In 2022, Gan et al. developed a finite-element analysis (FEA) model to verify the analytical model and investigate the magnetic damping behavior of BAW antennas [8]. In 2023, Dong et al. derived the magnetoelectric voltage gain based on Kirchhoff's current law to investigate the effect of two-phase thickness ratio on BAW antenna performance [9], and concluded that the BAW antenna achieves optimal energy coupling and conversion at a two-phase thickness ratio of 1:1. Although BAW antennas have achieved miniaturized devices and made some progress, the research focus remains concentrated on high-frequency bands, with no systematic study having been conducted on low-frequency bands.Based on this, this paper proposes a low-frequency laminated magnetoelectric composite antenna with a FeGaB/PZT-5H/FeGaB sandwich structure, analyzes its resonant frequency, stress distribution, and magnetic flux density modulus, thereby providing a research paradigm for bulk acoustic wave magnetoelectric antennas in the low-frequency band.

2 Basic Principle of Bulk Acoustic Wave Magnetoelectric Antennas

The bulk-acoustic-wave magnetoelectric antenna based on thin-film bulk acoustic resonators is a mechanical antenna fabricated from composite multiferroic materials, with strain-mediated magnetoelectric coupling effect as its core operating principle [10]. The magnetoelectric coupling effect is a product effect originating from the mutual coupling between the piezoelectric effect and the magnetostrictive effect [11], as illustrated in Figure 1.In the transmit mode, an alternating voltage is applied to the piezoelectric layer, generating strain via the inverse piezoelectric effect, which excites bulk acoustic wave resonance and converts electrical energy into mechanical vibration energy; the mechanical vibration is transferred to the magnetostrictive layer, inducing magnetization oscillations through the inverse magnetostrictive effect, which then radiates electromagnetic waves outward, achieving conversion from mechanical energy to electromagnetic energy.In the receive mode, the magnetostrictive layer responds to the magnetic field of the incident electromagnetic wave, converting the magnetic field energy into periodic mechanical strain via the magnetostrictive effect; this strain is then transferred to the piezoelectric layer through interlayer coupling, where the direct piezoelectric effect converts the mechanical vibration into an alternating voltage signal, achieving the inverse conversion from electromagnetic energy to electrical energy. Unlike conventional antennas that rely on far-field radiation, this magnetoelectric coupling effect governs radiation characteristics through acoustic-mechanical resonance, with the resonant frequency determined by bulk acoustic wave properties rather than the electromagnetic wavelength, thereby significantly reducing the antenna size and facilitating miniaturized design.

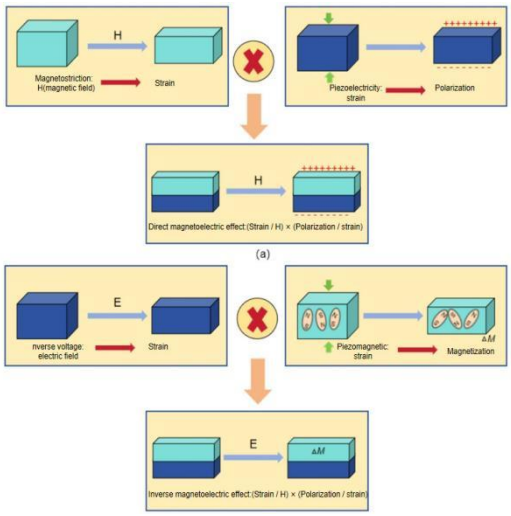


Figure 1 Principle diagram of the magnetoelectric coupling effect [11]

3 Simulation Analysis of Magnetoelectric Composite Antennas

Using COMSOL Multiphysics software, this work constructs a 3D magnetoelectric antenna with a cantilever beam structure—specifically, a beam-type antenna where one end is rigidly clamped and the other end is free—and performs analysis of its resonant frequency, stress distribution, and magnetic flux density magnitude. The computer used for the simulation is equipped with an Intel Core i7-13700 processor, 32 GB of RAM, and runs Windows 11, meeting the requirements for three-dimensional modeling of the laminated magnetoelectric composite antenna. Models including geometry, material, physical field and mesh were mainly constructed. In the geometric module, the magnetoelectric antenna adopts a magnetostriction-piezoelectricity-magnetostriction (Magnetostriction-Piezoelectricity-Magnetostriction) sandwich structure, namely the M-P-M sandwich laminated structure. As shown in Figure 2. Electrodes are placed on the upper and lower sides of the piezoelectric layer. The top surface of the upper electrode is set as the terminal, and the bottom surface of the lower electrode is defined as ground, thereby constructing a vertical excitation electric field across the piezoelectric layer. When an excitation voltage is applied to the electrodes, the piezoelectric material, being non-uniform and anisotropic, undergoes a certain deformation under the excitation of the applied electric field, thereby converting electrical energy into mechanical vibration. Meanwhile, the magnetoelectric composite antenna can achieve magnetoelectric coupling between the piezoelectric layer and the piezomagnetic layer through interlayer stress/strain transfer, thereby enabling conversion among electrical, mechanical, and electromagnetic energy. The model in this paper adopts the L-T(longitudinal-transverse)mode, in which the polarization of the middle piezoelectric layer is along the thickness direction, while the magnetization of the upper and lower magnetostrictive layers and the applied bias magnetic field are both along the length direction; that is, the laminated magnetoelectric composite is magnetized along the length direction and polarized along the thickness direction.

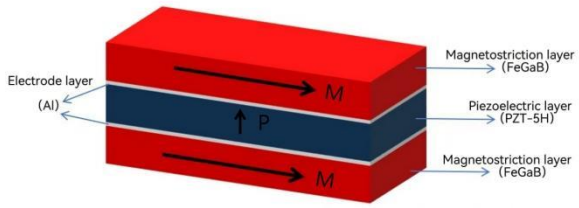


Figure 2 Structure of the magnetoelectric composite antenna

Considering the piezoelectric properties and magnetoelectric coupling characteristics of the materials, metallic Al is selected as the electrode and PZT-5H as the piezoelectric layer, with its material parameters listed in Table 1. We choose FeGaB for the magnetostrictive layer, with its material parameters listed in Table 2. The "Solid Mechanics" module selects the upper magnetostrictive layer, piezoelectric layer and lower magnetostrictive layer, which constitute the resonant structure of the magnetoelectric antenna; the "Electrostatics" module selects the piezoelectric layer. Subsequently, the antenna is meshed, and one of the broad sides of the magnetoelectric composite antenna is set with a fixed constraint; then, an air-domain sphere with a radius of 40 *mm* is created externally, and its spherical shell with a thickness of 1 *mm* is designated as an "infinite element domain" to simulate the infinite boundary conditions of free space, thereby preventing interference effects on the model and improving the validity of the simulation results.

Table 1 Material properties of PZT-5H [12]

Property	Value
Electromechanical coupling coefficient(%)	0.49
Dielectric constant	1700
Density(kg/m^3)	7500
Electrical conductivity（S/m）	20
Thermal conductivity	2.1

Table 2 Material properties of FeGaB [13, 14]

Property	Value
Density(kg/m3)	7500
Relative permittivity	1
Relative permeability	1300
Electrical conductivity（S/m）	2×10^{-5}
Poisson ratio	0.27
Young's modulus（GPa）	55
Initial permeability	200
Saturation magnetostriction coefficient（ppm）	70

From the intrinsic coupling mechanism of the BAW magnetoelectric composite antenna, the total potential energy of the antenna is positively correlated with the mechanical strain of the piezoelectric and piezomagnetic layers and the interlayer coupling stress, while the resonance peak corresponds to the maximum resonant vibration within the antenna, When the mechanical strain amplitude generated by the inverse piezoelectric effect and the interlayer transmitted stress both reach their maximum values, the alternating magnetization oscillation induced in the magnetostrictive layer via the inverse magnetostrictive effect is also maximized, and under this condition the antenna achieves optimal magnetoelectric coupling radiation performance [15]. The fundamental electromechanical coupling resonant response originates from the thickness-mode acoustic vibration of the composite resonant disk; its resonant frequency can be expressed by an analytical method as [16]:

$$f \propto \frac{1}{2S}\sqrt{\frac{E}{\rho}} \tag{1}$$

This is the thickness-mode resonance relation applicable to bulk acoustic wave resonators, such as those adopted in studies of FBAR ME antennas. Here, f is the resonant frequency, S denotes the physical thickness of the resonator; E and ρ represent Young's modulus and density of the piezoelectric material, respectively.

Based on the theoretical correlation between resonant frequency and device dimensions, together with the design principle that equal-thickness design of piezoelectric and magnetostrictive layers facilitates efficient energy conversion, we finalized the structural dimensions of the antenna through iterative simulation optimization. The size of the piezoelectric layer is $18mm\times 9mm\times 1mm$, and its normalized value with respect to the free-space electromagnetic wavelength is $\frac{1}{282342}\lambda_0 \times \frac{1}{564684}\lambda_0 \times \frac{1}{5082161}\lambda_0$, λ_0 denotes the wavelength of electromagnetic waves in free space at 59.03 kHz. The upper and lower magnetostrictive layers share the same dimensions of $18mm\times 9mm\times 1mm$ as the piezoelectric layer, and the electrodes are sized at $18mm\times 9mm\times 1mm$.

Figure 3 shows the total potential energy in COMSOL, peaking at 59.03 kHz, indicating significant resonance response and effective antenna design. This frequency is also the most efficient operating point for energy conversion, where internal stress is maximum, thus it is the resonant frequency (59.03 kHz).

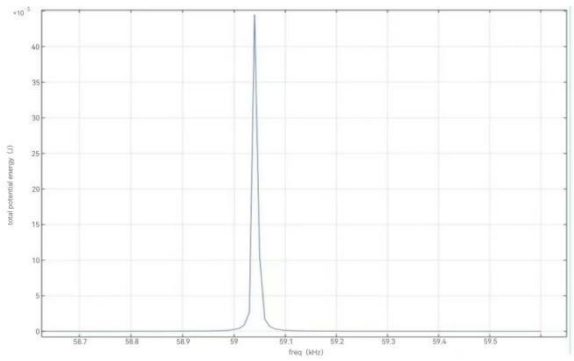


Figure 3 Total potential energy of the magnetoelectric composite antenna

In this paper, a fixed constraint is applied to one of the

broad sides of the magnetoelectric composite antenna to suppress rigid-body displacement of the model and ensure the stability of the resonant simulation calculation. Due to the fixed constraint, the stress in the antenna exhibits a clearly smooth decay distribution pattern, with large stress at the constrained end and small stress at the opposite side, as shown in Figure 4. The smoothly decaying stress distribution also demonstrates that stable and continuous strain transfer is achieved between the piezoelectric phase and piezomagnetic phase, which guarantees the energy conversion of magnetoelectric multi-field coupling.

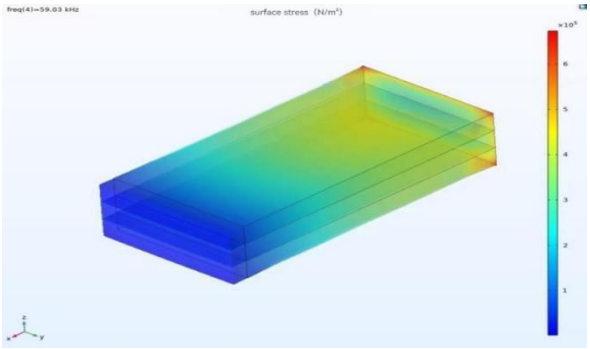


Figure 4 Stress distribution of the magnetoelectric composite antenna

Figure 5 shows the magnetic flux density modulus of the magnetoelectric composite antenna, which exhibits a radially outward spatial distribution centered on the antenna.Additionally, views of the magnetic flux density modulus from different perspectives provide visual support for the magnetic field distribution of the magnetoelectric composite antenna at the resonant frequency, helping to verify the effectiveness of the antenna design in electromagnetic radiation and energy conversion.

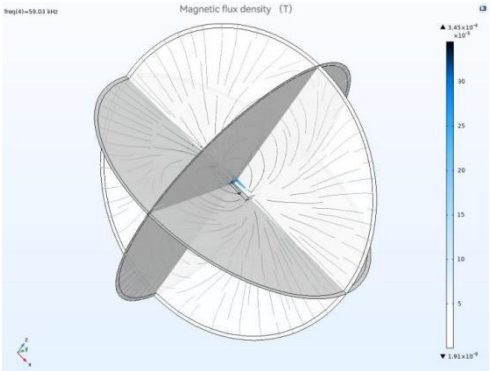


Figure 5 Magnetic flux density modulus of the magnetoelectric composite antenna

Figure 6 shows the side-view distribution of the magnetic flux density modulus of the magnetoelectric composite antenna at the resonant frequency of 59.03 kHz. From the figure, the minimum value of the magnetic flux density modulus is approximately 7.19×10^{-9} T, distributed in the peripheral region far from the antenna. The maximum value is 3.45×10^{-4} T, concentrated in the core region of the magnetoelectric antenna, indicating that the magnetic field energy gradually decays outward from the magnetoelectric coupling core region of the antenna. This is because the magnetostrictive material has high magnetic permeability, so the magnetic flux density modulus inside it is significantly higher than that in the surrounding space; this phenomenon also indicates that the alternating magnetic field is highly concentrated inside the antenna, consistent with the typical spatial distribution pattern of magnetic field radiation for magnetoelectric antennas.

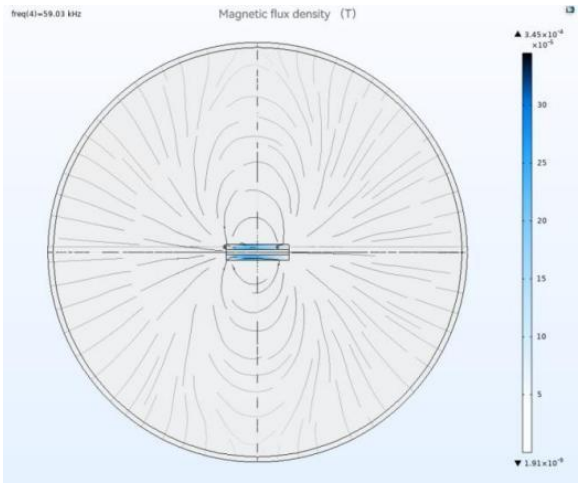


Figure 6 Side view of the magnetic flux density modulus of the magnetoelectric composite antenna

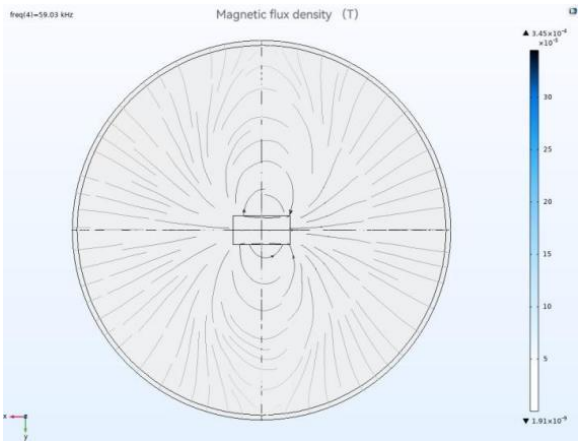


Figure 7 Top view of the magnetic flux density modulus of the magnetoelectric composite antenna

Figure 7 shows the top-view distribution of the magnetic flux density modulus of the magnetoelectric composite antenna at the resonant frequency of 59.03 kHz, i.e., the top view of the magnetoelectric composite antenna. The magnetic field is mainly concentrated around the magnetostrictive layer, with a clockwise distribution on the upper side and a counterclockwise distribution on the lower side; both the upper and lower sides achieve head-to-tail connectivity of the antenna's magnetic field in three-dimensional space, meaning that the magnetic field lines inside the antenna extend from one end to the other along the length direction, loop through the external space, and return to the starting point, forming a closed magnetic field line loop.

Table 3 compares this antenna with three typical miniaturized antennas in operating frequency and size. The designed antenna achieves much smaller dimensions at a similar band, showing superior miniaturization.

Table 3 Comparison of antenna parameters

References	Antenna type	Working frequency (kHz)	Feeding method	Antenna dimensions (mm)	Normalized dimension
[17]	Ferrite-core loop antenna	30	Current excitation + LC impedance matching	100×100×21	$\frac{1}{100000}\lambda_0 \times \frac{1}{100000}\lambda_0 \times \frac{1}{476190}\lambda_0$
[18]	Nanocrystalline-core loop antenna	15	High-current excitation + isolation transformer	85×85×30	$\frac{1}{235294}\lambda_0 \times \frac{1}{235294}\lambda_0 \times \frac{1}{66667}\lambda_0$
This work	Layered magnetoelectric composite antenna	59.03	Piezoelectric voltage excitation	18×9×3.2	$\frac{1}{282342}\lambda_0 \times \frac{1}{564684}\lambda_0 \times \frac{1}{5082161}\lambda_0$

4 Conclusion

This paper designs a laminated magnetoelectric composite antenna with a FeGaB/PZT-5H/FeGaB sandwich structure, providing an effective research paradigm for the design of bulk acoustic wave magnetoelectric antennas in the low-frequency band. Through three-dimensional finite element simulation, the resonant frequency, stress distribution, and magnetic flux density of the antenna are investigated, and the resonant frequency is determined to be 59.03 kHz, demonstrating that at this frequency, the magnetoelectric coupling efficiency between the piezoelectric and piezomagnetic layers is maximized and the antenna's radiation performance is optimal. Simulation results verify the effectiveness of the antenna design. This design breaks through the size limitation of conventional antennas and possesses broad application prospects, especially in low-frequency Internet of Things, low-power wireless communication and miniature radio-frequency terminals.

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