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# Design of a low-frequency miniaturized piezoelectric antenna based on acoustically actuated principle

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An acoustically actuated piezoelectric antenna is proposed for low frequency (LF) band in this paper. The proposed antenna is theoretically calculated, numerically optimized by the finite element method (FEM), and experimentally analyzed. The measurement results show that the near-field radiation pattern of the piezoelectric antenna is similar to that of the electric dipole antenna. The radiation efficiency of the piezoelectric antenna is 3−4 orders of magnitude higher than that of electrically small antenna (ESA), with their sizes being the same size, and the maximum transmission distance obtained experimentally is 100 cm, which can be improved by increasing the input power. In addition, the gain, directivity, and quality factor of piezoelectric antenna are also analyzed. In this paper, traditional antenna parameters are creatively used to analyze the performance of piezoelectric antenna. The research conclusions can provide reliable theoretical basis for realizing LF antenna miniaturization.

**Keywords:** piezoelectric low frequency antenna, resonance frequency, radiation quality factor, antenna miniaturization

**PACS:** 77.65.Dq, 77.65.–j, 84.40.Ba, 92.60.Ta **DOI:** 10.1088/1674-1056/ac6495

## 1. Introduction

Low frequency (LF) antenna has been widely used in meteorological broadcast, radio navigation, radio frequency identification, and underwater communication because of its high penetrability and low attenuation rate.[1–5] The LF antenna has longer wavelength (1 km–10 km) than the high-frequency antenna, its transmission loss is not sensitive to water, nor rock, nor soil, and it has excellent penetrability and long-distance transmission performance. Therefore, the LF antenna is suitable for underwater communication and object detection in rocks and soil.[6,7] In addition, the LF antenna has strong anti-interference capability and is less disturbed by ionospheric disturbance, which makes the LF antenna very suitable for long-distance transcontinental communication.[8,9]

However, the traditional antenna relies on electromagnetic wave resonance, and its size is generally larger than the wavelength of electromagnetic wave. It is difficult to achieve a size reduction of orders of magnitude, thus it is difficult to apply to portable devices, wireless sensor networks and the IoT.[1–11] For example, the 60-kHz WWVB antenna built by the National Institute of Standards and Technology (NIST) has a large size and is supported by a 122-m high tower.[12] The cost of traditional LF antenna is very high. Therefore, the key challenge to the LF antenna is its miniaturization. In response to the problem of antenna miniaturization, researchers are committed to studying various methods to achieve antenna miniaturization, including loading technology, broadband matching network technology, high permittivity, and high permeability materials, electromagnetic metamaterials technology.[13–16] These methods can effectively achieve antenna miniaturization at the expense of performance, such as radiation efficiency and bandwidth. In addition, these methods are usually only applicable to high frequency band and above. These methods are not suitable for antenna design in LF nor VLF.

In recent years, some researchers have proposed antennas that are different from the traditional radiation antenna in principle. By using the material properties of magnetostrictive material or piezoelectric material, the electromagnetic radiation is excited by the acoustic wave. At the same frequency, the acoustic wavelength is much smaller than the electromagnetic wavelength in solid.[17] The theoretical limit of traditional antenna miniaturization has been broken through. In Ref. [18], the working frequency of the proposed piezoelectric transmitter could be 5 orders of magnitude lower than that of the electrically small antenna (ESA) of the same size. In Ref. [19], the electromagnetic radiation of the piezoelectric resonator was analyzed under symmetry breaking. The results show that the radiation is significantly enhanced under asymmetric excitation. In Ref. [20], the LF piezoelectric transmitter with a resonance frequency of 35 kHz was proposed, which is composed of $LiNbO_3$ crystal with a length of 9.4 cm and diameter of 1.6 cm. The experimental results show that it has higher radiation efficiency than electric dipole antenna. In Ref. [21],

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the very low frequency (VLF, 3 kHz–30 kHz) communication system was designed by using a pair of magnetoelectric antennas. The near-field radiation of magnetoelectric antenna is equivalent to that of a magnetic dipole antenna. In Ref. [22], the magnetostrictive/piezoelectric heterostructures were used to radiate and receive very high frequency (VHF, 30 MHz–300 MHz) and ultra-high frequency (UHF, 0.3 GHz–3 GHz) electromagnetic waves, and it was verified that a thin film multiferroic material with micron thickness can be used to achieve a miniaturized antenna working in GHz frequency.

The existing research results show that the piezoelectric antenna can realize the effective energy conversion between bulk acoustic wave and electromagnetic wave through the piezoelectric effect. The impedance of the piezoelectric antenna can be easily matched to the driven electronic device, eliminating the need for large and inefficient matching circuit. Solving the problems of antenna miniaturization and high power loss is greatly significant, and has become a research hotspot in antenna miniaturization design. However, in the current research on piezoelectric antennas the theoretical analysis methods are mainly used from the perspective of material characteristics, and the piezoelectric antenna is rarely measured from the performance index of the traditional antenna.

In this paper, we present a miniaturized LF piezoelectric antenna by using lead zirconate titanate (PZT) as a piezoelectric material. The transmission efficiency, gain and directivity of the piezoelectric antenna are analyzed and compared with those of ESA, with their sizes being the same. In addition, based on the finite element method (FEM), the influence of piezoelectric antenna size on its resonance frequency is analyzed, and the main factors affecting the resonance frequency of piezoelectric antenna are determined. Some valuable conclusions are obtained, which lays the foundation for designing the LF miniaturized piezoelectric antenna.

## 2. Piezoelectric antenna design theory, structure, and methods

### 2.1. Radiation principle and structure of piezoelectric antenna

The accelerated motion of charge, including the oscillation of dipole moment, can radiate electromagnetic radiation. Using this principle, any element containing time-varying dipole moment, such as piezoelectric material, can be considered as a radiator. In the piezoelectric antenna the piezoelectric materials such as piezoelectric crystal and piezoelectric ceramics are used as a main radiator. Based on the piezoelectric effect of piezoelectric material, the mechanical properties and electrical properties of piezoelectric material can be converted into each other. When the piezoelectric antenna is excited by the external electric field, the mechanical stress inside the piezoelectric antenna is generated. With the influences from deformation caused by the mechanical stress, the positive and negative charges in the piezoelectric antenna are shifted, resulting in an induced current. Therefore, with the influence of time-varying excitation, the polar state of surface charge of piezoelectric antenna will change continuously, which is equivalent to the oscillation of electric dipole moment, generating electromagnetic radiation. The radiation principle is shown in Fig. 1.

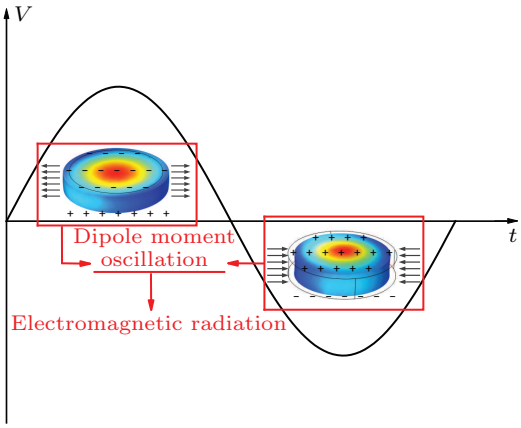



**Fig. 1.** Radiation principle of piezoelectric antenna.

The piezoelectric antenna results in electric polarization with surface charge density $\sigma_q$, which can be calculated from the following equation:[23]

$$\sigma_q = dT = dC^E S, \tag{1}$$

$$I = \sigma_q A\omega = dC^E SA\omega, \tag{2}$$

where $d$ is the piezoelectric strain constant, $T$ is the applied stress, $C^E$ is the stiffness at constant electric field, $S$ is the resulting strain, $A$ is the surface area of the accumulated charges, and $\omega$ is the angular frequency. Equation (1) calculates the surface charge density $\sigma_q$ under the average strain in the entire piezoelectric material volume. The effective surface dipole current $I$ is calculated from Eq. (2).

The generated magnetic induction intensity in a far-field region can be described as[24]

$$|B_{far}| = \frac{IL\omega}{4\pi\varepsilon_0 c^3 R}, \tag{3}$$

where $I$ is the surface dipole current, $L$ represents dipole moment length, $\varepsilon$ is the permittivity of the free space, $c$ is the speed of light, and $R$ is the distance between the observed point and the center of the piezoelectric antenna.

In order to analyze the radiation performance of the piezoelectric antenna, we design a disc-type piezoelectric antenna as shown in Fig. 2. The material is composed of PZT with a diameter of 50 mm and height of 10 mm, and its polarization direction is along the thickness direction. The top and

bottom of the PZT disc are plated silver electrodes with 20 μm in thickness. The two wires are welded to the top silver electrode and bottom silver electrode of the PZT disc to provide electrical excitation, and the length of the wires is minimized to reduce the near-field radiation from the current loop.

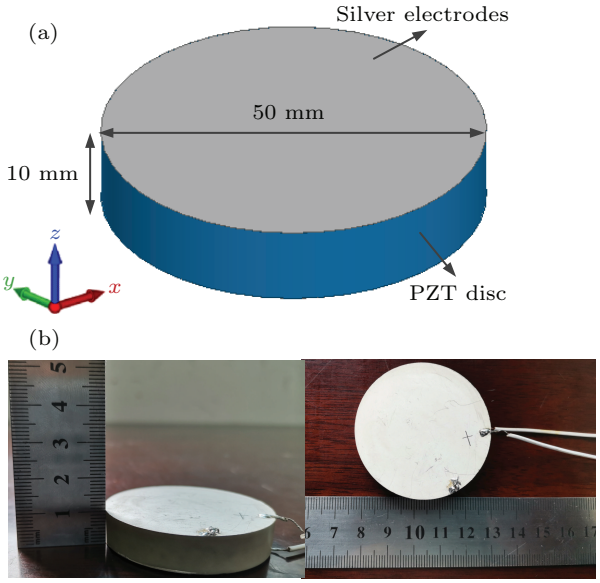



**Fig. 2.** (a) Schematic diagram of piezoelectric antenna and (b) prototype picture of piezoelectric antenna.

### 2.2. Analysis methods of piezoelectric antenna

The main resonance module of the piezoelectric antenna is bulk acoustic resonator, which involves the solutions of multiple physical fields such as acoustic field, electromagnetic field, and stress field, and the finite element method (FEM) can well solve the coupling problem of multiple physical fields. Therefore, the COMSOL Multiphysics finite element software is used to simulate the resonance frequency, stress, and displacement of the piezoelectric antenna. The structure and size of piezoelectric antenna are shown in Fig. 2. The simulation modules include the solid mechanics and electrostatics modules. Firstly, the resonance frequency of piezoelectric antenna is calculated by eigenfrequency simulation, and then the parameters of piezoelectric antenna are simulated in frequency domain, such as stress/strainand displacement, admittance. For the frequency–domain simulation, the electrical boundary conditions and mechanical boundary conditions need setting. Electrically, the voltage amplitude is applied to the top electrode while the bottom electrode is grounded. In terms of mechanics, a free boundary condition is applied to the whole PZT disc to reduce any anchor damping, and material damping is specified for PZT. The simulation result is shown in Fig. 3.

It can be seen from Fig. 3 that the resonance frequency of the piezoelectric antenna is 36.4 kHz. At the resonance frequency, the maximum stress of the piezoelectric antenna is 30 kPa, which is distributed in the center of the piezoelectric antenna. The maximum displacement of piezoelectric antenna is $5.5\times10^{-6}$ mm, and the main part is distributed on the edge of the piezoelectric antenna. It can be seen from Fig. 3(b) that the vibration pattern of the piezoelectric antenna is radial vibration. For the radial vibration of piezoelectric disc, its resonance frequency is calculated from Eq. (4) to be 37 kHz.[25,26]

$$f_{\mathrm{r}} = \frac{\eta_1}{2\pi r}\sqrt{\frac{1}{\rho S_{11}^{\mathrm{E}}\sqrt{1-(\sigma^{\mathrm{E}})^2}}}, \tag{4}$$

where $\eta_1$ is a function of $\sigma^{\mathrm{E}}$, and its value is $1.86+0.633\sigma^{\mathrm{E}}$, with $\sigma^{\mathrm{E}}$ being the Poisson ratio of the PZT zero electric field, and its value being 0.36; $r$ is the radius of the PZT disc, and its value is 25 mm; $\rho$ represents the density of the PZT, and its value is 7600 kg/m$^3$; $S_{11}^{\mathrm{E}}$ is the elastic compliance at the constant electric field in the loading direction of the PZT, and its value is $18.2\times10^{-12}$ m$^2$/N. Equation (4) indicates that after the material of the PZT disc is determined, the resonance frequency of the PZT disc with radial vibration depends on its radius.

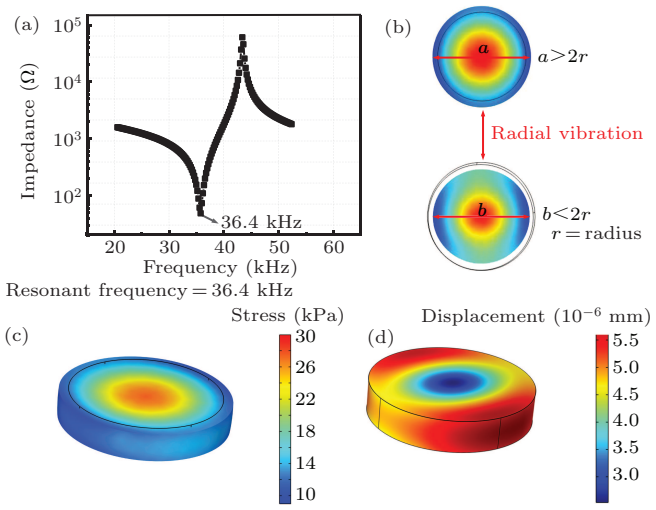



**Fig. 3.** FEM-calculated characteristics of piezoelectric antenna: (a) resonance frequency, (b) vibration radial pattern, (c) stress distribution at resonance frequency, and (d) displacement distribution at resonance frequency.

In addition, the modified Butterworth–van Dyke (MBVD) model is widely used for designing the bulk acoustic wave resonator, bulk acoustic wave filters and piezoelectric antennas because the model is simple and the parameter is easy to be extracted. The model consists of six elements as shown in Fig. 4. The MBVD equivalent model represents the material or structural parameters of the piezoelectric antenna in the form of *RLC* lumped elements, which can more accurately reflect the electrical characteristics of the piezoelectric antenna. Combined with Advanced Design System (ADS) simulation software produced by Agilent, the piezoelectric antenna can be optimally designed accurately and efficiently.

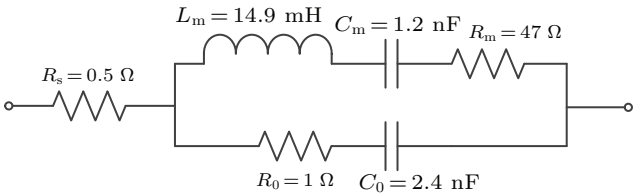



**Fig. 4.** MBVD equivalent circuit of piezoelectric antenna.

Here $C_m$, $L_m$, and $R_m$ are the motional capacitance, motional inductance, and motional resistance respectively; $R$ is the dielectric loss in the piezoelectric materials; $R_s$ represents the electrode loss and lead loss; $C$ is the static capacitance, which represents the dielectric characteristic of the resonator.[27] The resonance frequency of the piezoelectric antenna calculated by the MBVD equivalent circuit is 37.6 kHz as shown in Fig. 5.

In order to verify the correctness of resonance frequency calculated by the FEM, analytical method and MBVD equivalent circuit method, and also to test the radiation performance of the piezoelectric antenna, the experimental test platform for piezoelectric antenna is established in this work as shown in Fig. 6. Firstly, the sine wave signal is generated by the signal generator, which is amplified by a power amplifier and loaded into the piezoelectric antenna to generate the alternating current (AC) electromagnetic waves. The electromagnetic wave is received by the copper coil and transmitted to the oscilloscope to display in the form of voltage signal. The copper coil is made of enamelled wire with a diameter of 0.35 mm, and the number of turns is 1000. According to the law of electromagnetic induction, the induced voltage of the copper coil is proportional to the magnitude of the alternating magnetic field. The unknown alternating magnetic field can be calculated by measuring the output voltage of the copper coil. The resonance frequency of the experimental test is shown in Fig. 5, and the resonance frequency is 37.9 kHz.

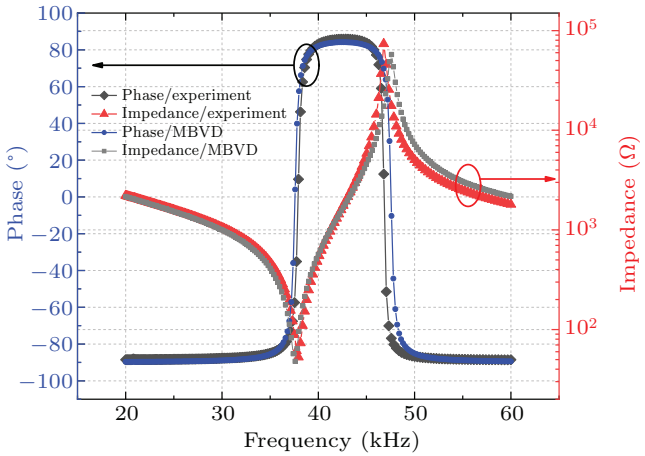



**Fig. 5.** Impedance and phase *versus* frequency of MBVD equivalent circuit and experimental test.

In summary, the FEM, analytical method, MBVD equivalent circuit method, and experimental test are used to analyze the resonance frequency of the piezoelectric antenna. The resonance frequencies calculated by the four methods are listed in Table 1.

**Table 1.** Resonance frequencies calculated by four methods.

| Calculated methods | FEM | Analytical method | MBVD equivalent circuit method | Experimental test |
|---|---|---|---|---|
| Resonance frequency (kHz) | 36.4 | 37 | 37.6 | 37.9 |
| Error (%) | 4.1 | 2.4 | 0.8 | 0 |

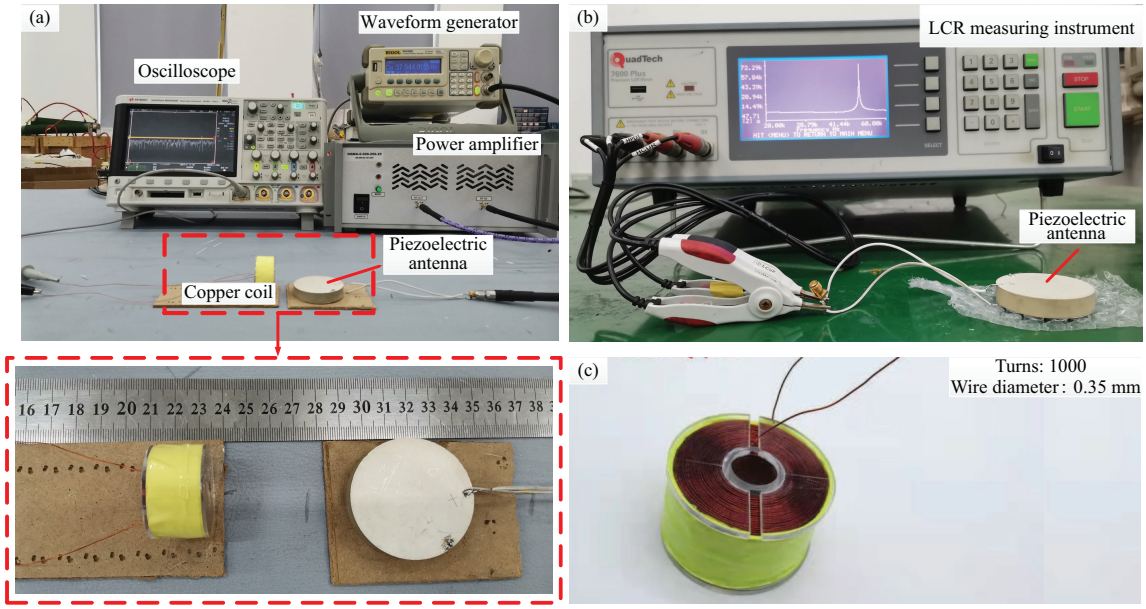



**Fig. 6.** (a) Electromagnetic radiation test platform and (b) impedance test platform for piezoelectric antenna, and (c) magnetic field receiver.

It can be seen from Table 1 that the resonance frequency calculated by the FEM is the smallest, and the error may be caused by processing technology and electrode loss. Based on the test results, the resonance frequency error calculated by the four methods is less than 4.1%, which verifies the correctness of the FEM, the analytical method and the MBVD equivalent circuit method to calculate the resonance frequency.

## 3. Influence of piezoelectric antenna size on resonant frequency

The resonance frequency of the piezoelectric antenna directly affects the radiation characteristics and operating frequency band. In the previous section, the correctness of the FEM based on COMSOL Multiphysics to calculate the resonant frequency of the piezoelectric antenna is verified. In this section, the FEM is used to analyse the variation of the resonant frequency from the aspect of dimensional design.

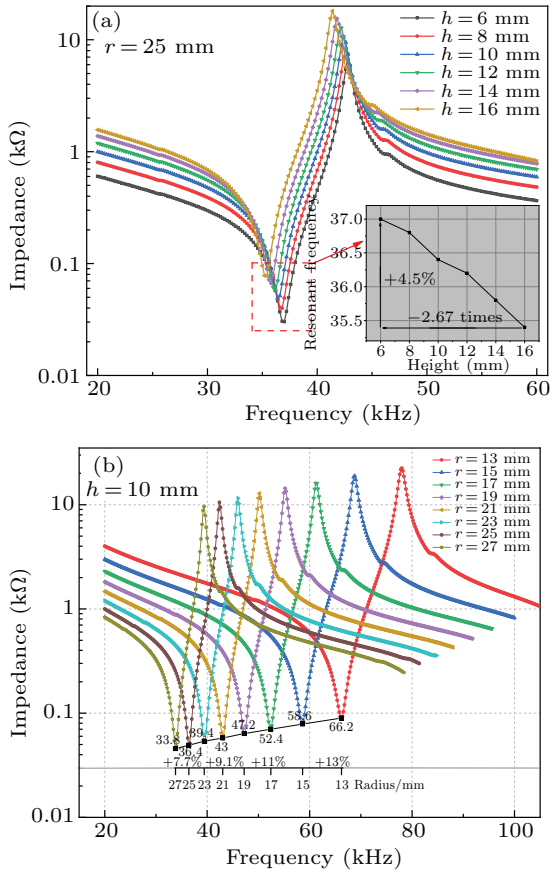



**Fig. 7.** (a) Variations of piezoelectric antenna resonant frequency with (a) height and (b) radius.

The variations of resonance frequency of piezoelectric antenna with height and radius are obtained as shown in Fig. 7. Figure 7(a) shows the variations of the resonant frequency with the height of the piezoelectric antenna when the radius is a constant of 25 mm. It can be seen that the resonance frequency increases with the decrease of the height of the piezoelectric antenna, but the resonant frequency increases slowly. When the height is reduced by 2.6 times, the resonant frequency is increased by only 4.5%. It can be seen that the resonance frequency of piezoelectric antenna with radial vibration is not sensitive to height change. Figure 7(b) shows the variations of resonance frequency with the radius of piezoelectric antenna when the height is a constant of 10 mm. It can be seen that the resonance frequency has a nonlinear inverse relationship with the radius of piezoelectric antenna. When the radius of the piezoelectric antenna is 27 mm, the resonance frequency is 33.8 kHz. When the radius is reduced to 13 mm, the resonance frequency is 66.2 kHz, which increases nearly twice. The resonant frequency is more sensitive to the variation of radius than to the variation of height. In addition, with the decrease of radius value, the range of the resonance frequency gradually increases when the radius is reduced to the same extent. When the radius is reduced from 27 mm to 25 mm, the resonance frequency increases by 7.7%, and when the radius is reduced from 15 mm to 13 mm, the resonance frequency increases by 13%. In summary, the target frequency of piezoelectric antenna can be optimized by adjusting PZT radius.

## 4. Transmission magnetic field, efficiency, and radiation pattern

### 4.1. Analysis of transmission magnetic field and maximum transmission distance

Piezoelectric antenna has strict requirements for transmission distance in the applications in ground communication and submarine communication. Therefore, it is of great significance to study the distance between receiving coil and piezoelectric antenna.

Firstly, the radiation magnetic fields of the piezoelectric antenna with different input power values are analyzed, and the radiation magnetic fields at different input power values are measured at 5cm as shown in Fig. 8(a). Secondly, the maximum transmission distances of piezoelectric antenna at different input power values are analyzed as shown in Fig. 8(b). Finally, when the input power is 0.4 W, the attenuation degree of the radiated magnetic field with distance is analyzed as shown in Fig. 8(c).

It can be seen from Fig. 8(a) that as the input power of the piezoelectric antenna increases, the radiated magnetic field of the piezoelectric antenna increases. When the input power is 0.016 W, the radiated magnetic field of piezoelectric antenna is 2.91 nT; when the input power is 0.4 W, the radiated magnetic field of piezoelectric antenna is 17.22 nT. When the input power increases by 25 times, the radiated magnetic field is increased by 6 times. It can be seen from Fig. 8(b) that as the input power of the piezoelectric antenna increases, the maximum transmission distance of the piezoelectric antenna increases. When the input power is 0.016 W, the maximum transmission distance of the piezoelectric antenna is 12 cm. When the

power is 0.25 W, the maximum transmission distance of the piezoelectric antenna is 50 cm, and the maximum transmission distance increases by 4.2 times. In summary, when the piezoelectric antenna is designed, the transmission magnetic field and transmission distance can be improved by increasing the input power of the piezoelectric antenna.

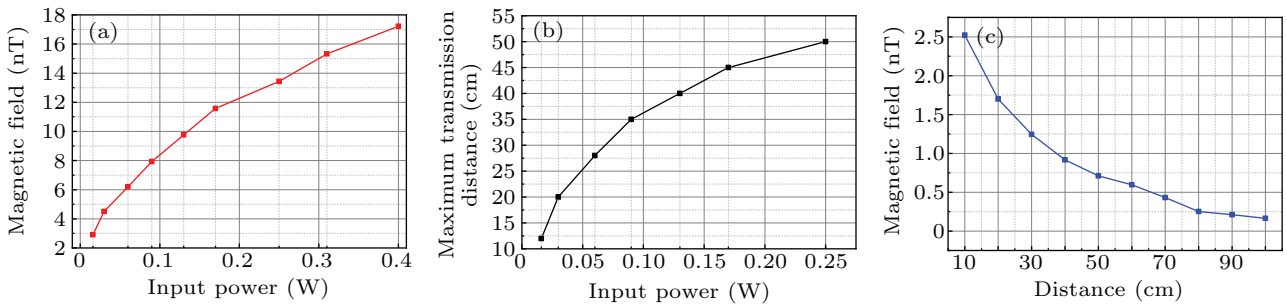



**Fig. 8.** Transmission characteristics of piezoelectric antenna, showing (a) variation of radiated magnetic field with input power; (b) variation of maximum transmission distance with input power of piezoelectric antenna; (c) variation of the radiated magnetic field with distance.

Figure 8(c) shows the radiated magnetic fields of the piezoelectric antenna at different distances between the piezoelectric antenna and the receiving coil. It can be found that the radiated magnetic field of the piezoelectric antenna decreases significantly with the increase of distance. When the distance is 10 cm, the radiated magnetic field of the piezoelectric antenna is 2.52 nT. When the distance is 50 cm, the radiated magnetic field of the piezoelectric antenna is 0.71 nT. The radiated magnetic field of the piezoelectric antenna is reduced by 3.5 times. When the distance is increased to 100 cm, the radiated magnetic field of the piezoelectric antenna is 0.16 nT, which is 15.7 times lower than the counterpart when the distance is 10 cm. In addition, the curve fitting of Fig. 8(c) shows that the attenuation relationship of the magnetic field radiated by the piezoelectric antenna with distance is $1/r^{1.5}$, which slightly deviates from the theoretical value of electric dipole antenna. This is because of the influence of the experimental cable on the radiated magnetic field. The theoretical value of electric dipole antenna is $1/r^2$. It is verified that the radiation pattern of the piezoelectric antenna is similar to that of the electric dipole antenna.

### 4.2. Analysis of piezoelectric antenna radiation efficiency

The antenna efficiency needs measuring in the far-field radiation pattern of the antenna. However, it is very difficult for the LF piezoelectric antenna with large wavelength. At present, most of microwave anechoic chambers support only the measurement of antennas above UHF. Under these constraints, the radiation efficiency of the piezoelectric antenna is deduced by comparing with the ESA.

In the lossy antenna system, the radiation efficiency can be calculated from the following equation:[28,29]

$$\begin{cases} \eta = \dfrac{Q_{\mathrm{t}}}{Q_{\mathrm{A}}}, \\ Q_{\mathrm{t}} = \dfrac{1}{1/Q_{\mathrm{m}} + 1/Q_{\mathrm{A}}}, \end{cases} \tag{5}$$

where $Q_{\mathrm{t}}$ is the total quality factor; $Q_{\mathrm{m}}$ encompasses all non-radiation losses within the antenna system; $Q_{\mathrm{A}}$ is the radiation quality factor for the piezoelectric antenna.

In the piezoelectric antenna, $Q_{\mathrm{m}}$ is much less than $Q_{\mathrm{A}}$, so the total quality factor $Q_{\mathrm{t}}$ of the piezoelectric antenna is approximately equal to $Q_{\mathrm{m}}$.[30,31] Therefore, the radiation efficiency of the piezoelectric antenna can be simplified into $\eta \approx Q_{\mathrm{m}}/Q_{\mathrm{A}}$. The $Q_{\mathrm{m}}$ can be obtained experimentally. The QuadTech's Precision LCR Meter of Fig. 6(b) is used to measure the resonance frequency $f_{\mathrm{s}}$, dynamic resistance $R_{\mathrm{m}}$ and dynamic capacitance $C_{\mathrm{m}}$ of piezoelectric antenna. Their values are 37.9 kHz, 1.2 nF, and 47 Ω, respectively. From the following equation, the $Q_{\mathrm{m}}$ of piezoelectric antenna is calculated to be 74.5,

$$Q_{\mathrm{m}} = \frac{1}{2\pi f_{\mathrm{r}} C_{\mathrm{m}} R_{\mathrm{m}}} = 74.5. \tag{6}$$

In order to calculate $Q_{\mathrm{A}}$, it is assumed that the radiation pattern of piezoelectric antenna is equivalent to that of the electric dipole antenna. The attenuation relationship of magnetic field with distance is close to $1/r^2$ in Fig. 8(c), which verifies the rationality of the hypothesis. The $Q_{\mathrm{A}}$ is calculated based on two different methods to ensure its accuracy. McLean gives the minimum value of $Q_{\mathrm{A}}$ for ESA,[32]

$$Q_{\mathrm{A,min}} = 1/(ka)^3 + 1/ka, \tag{7}$$

where $Q_{\mathrm{A}}$ is the radiation quality factor; $k$ is the wavenumber, and a is the enclosing sphere centered on the antenna. With a $ka$ value of $2.03\times10^{-5}$, the calculated $Q_{\mathrm{A,min}}$ is about $1.2\times10^{14}$. In addition, Thiele *et al.* comprehensively considered the directivity and far-field radiation of the ESA, and gave a more accurate calculation formula of $Q_{\mathrm{A,min}}$ as follows:[33]

$$\begin{cases} Q_{\mathrm{A,min}} = \dfrac{\int_{-\infty}^{-\pi L/\lambda} |E_n(u)|^2 \,\mathrm{d}u + \int_{\pi L/\lambda}^{\infty} |E_n(u)|^2 \,\mathrm{d}u}{\int_{-\pi L/\lambda}^{\pi L/\lambda} |E_n(u)|^2 \,\mathrm{d}u}, \\ E_n(u) = \dfrac{\cos u - \cos(\beta L/2)}{[1-\cos(\beta L/2)]\cdot\sqrt{1-(2u/\beta L)^2}}. \end{cases} \tag{8}$$

The $Q_{\mathrm{A,min}}$ can be calculated from Eq. (8), and its value of is $1.2\times10^{15}$. Therefore, we assume that the value of $Q_{\mathrm{A}}$ is between $1.2\times10^{14}$ and $1.2\times10^{15}$. From Eq. (5), the radiation efficiency of piezoelectric antenna is calculated to be $6.2\times10^{-13}$–$6.2\times10^{-14}$.

The radiation efficiency of the electric dipole antenna with the same size as the piezoelectric antenna is calculated from the following equation:[34]

$$\eta_{\mathrm{A}}=\frac{R_{\mathrm{r}}}{R_{\mathrm{r}}+R_{\mathrm{L}}}\approx\frac{40\pi^2\left(l/\lambda\right)^2}{40\pi^2\left(l/\lambda\right)^2+A\lambda/4l}\approx7.1\times10^{-16},\quad(9)$$

where $R_{\mathrm{r}}$ is the radiation resistance, and $R_{\mathrm{L}}$ is the loss resistance. It can be seen that the radiation efficiency of the electric dipole antenna is very low, which is $7.1\times10^{-16}$. The reason is that when the antenna size is reduced, the radiation resistance decreases, which narrows the working bandwidth and reduces the radiation efficiency. This also is the challenge to traditional antenna miniaturization.

Therefore, the piezoelectric antenna can well solve the problem of traditional antenna LF miniaturization. The radiation efficiency of piezoelectric antenna is 2–3 orders of magnitude higher than that of the electric dipole antenna of the same size. It is confirmed that the proposed piezoelectric antenna has better radiation performance.

### 4.3. Radiation pattern, directivity, and gain

In order to measure the radiation pattern of the piezoelectric antenna, we assume that the thickness direction of the piezoelectric antenna is along the $y$ axis as shown in Fig. 9. The radiation pattern of piezoelectric antenna is measured by sweeping the elevation angle $\theta$ in the $x$–$o$–$z$ plane and $x$–$o$–$y$ plane. The measurement distance is 10 cm, and the input power of the piezoelectric antenna is 0.4 W. The radiation pattern is shown in the form of normalized output magnetic field, and the directions of the two planes are shown in Fig. 9.

It can be seen from Fig. 9 that the radiation patterns of the piezoelectric antenna in the $x$–$o$–$z$ plane and $x$–$o$–$y$ plane are similar to those of electric dipole antenna. When $\theta=90^\circ$ and $\theta=270^\circ$, the magnetic field values are the largest, and the minimum values appear at $\theta=0^\circ$ and $\theta=180^\circ$. It is worth noting that the magnetic fields are zero at $\theta=0^\circ$ and $\theta=180^\circ$ after normalization, and there is a small magnetic field in the actual measurement. This is because the piezoelectric antenna is affected by the environmental magnetic field in the measurement, and it cannot be equivalent to the ideal electric dipole antenna.

The directivity of piezoelectric antenna is also an important performance parameter, and the directivity of the piezoelectric antenna can be estimated frm the following equation:

$$\begin{cases}D=\dfrac{4\pi U_{\max}}{P_{\mathrm{rad}}}=\dfrac{2\pi\,\mathrm{Re}\left[E_\theta\times H_\varphi^*\right]\cdot r^2\hat{r}}{P_{\mathrm{rad}}},\\ P_{\mathrm{rad}}=\dfrac{\mu_0\left|p_{\mathrm{e}}\right|^2\omega^4}{12\pi c},\end{cases}\quad(10)$$

where Re is the real part of the complex number, $E$ and $H$ represent the electric field and magnetic field respectively, $\theta$ and $\varphi$ denote spatial azimuth angles, $r$ is the distance from the field point to the coordinate origin, $\hat{r}$ is the radial unit vector, $U_{\max}$ is the maximum radiation intensity, $P_{\mathrm{rad}}$ is the total radiated power, $p_{\mathrm{e}}$ is the electric dipole moment, $\mu$ is the vacuum permeability, $\omega$ is the angular frequency, and $c$ is the speed of light in vacuum.

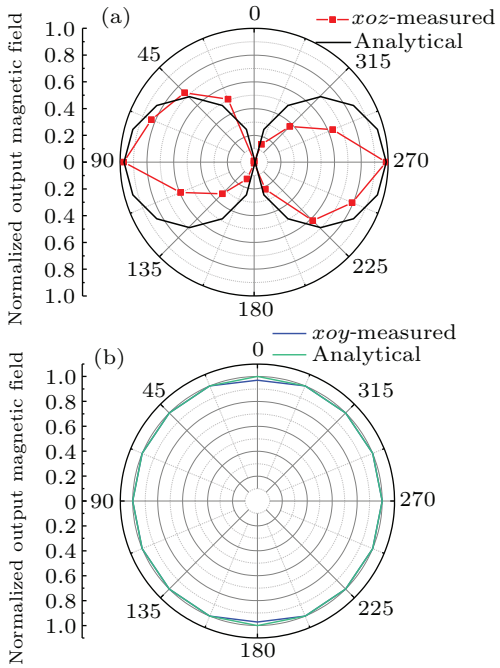



**Fig. 9.** Radiation patterns of piezoelectric antenna in (a) $x$–$o$–$z$ plane, and (b) $x$–$o$–$y$ plane.

From Eq. (9), it can be calculated that the directivity of the piezoelectric antenna is 1.63. The antenna gain and the directivity is related by $G=\eta D$. The radiation efficiency of piezoelectric antenna is $6.2\times10^{-14}$, and the gain of the piezoelectric antenna is $G=-130$ dBi.

In summary, we have analyzed the radiation performance of the piezoelectric antenna. The efficiency, gain and directivity of the proposed piezoelectric antenna are $6.2\times10^{-13}$–$6.2\times10^{-14}$, $-130$ dBi, and 1.63 respectively.

## 5. Conclusions and perspectives

In this paper, an LF miniaturized piezoelectric antenna is proposed, and the variation of radiation pattern is analyzed experimentally. The main factors affecting the resonant frequency of piezoelectric antenna are determined. In addition, we innovatively use the traditional antenna parameters, such as

radiation efficiency, directivity and gain to analyze the piezoelectric antenna. Some conclusions are obtained below.

(i) The resonance frequency of piezoelectric antenna has nonlinear inverse relationship with its height and radius, but the disc radius is the main factor affecting the resonant frequency. In addition, with the radius value decreases, the range of the resonant frequency significantly increases when the radius size is reduced to the same extent. In summary, for the piezoelectric antenna with radial vibration, we can optimize the radius size to make the piezoelectric antenna work at different resonant frequencies and broaden the working frequency band of the piezoelectric antenna.

(ii) With the increase of transmission distance, the radiation magnetic field of piezoelectric antenna decreases significantly. The attenuation relationship of the magnetic field is close to $1/r^2$, which is similar to the electric dipole antenna. With the increase of the input power of the piezoelectric antenna, the magnetic field and the maximum transmission distance also increase. The maximum transmission distance with input power of 0.4 W is 100 cm. However, the transmission distance of the piezoelectric antenna can be improved by increasing the input power. It makes piezoelectric antenna have greater application value in LF long-distance communication.

(iii) The piezoelectric antenna can solve the problem of LF miniaturization of traditional antenna. The radiation efficiency of the piezoelectric antenna is 2–3 orders of magnitude higher than that of the electric dipole antenna, with their sizes being the same, which confirms that the proposed piezoelectric antenna has better radiation performance. The radiation pattern of the piezoelectric antenna further verifies that the radiation pattern of the piezoelectric antenna is similar to that of the electric dipole antenna. In addition, the directivity and gain of the piezoelectric antenna are calculated, which are $D \approx 1.63$ and $G = -130$ dBi respectively.

The piezoelectric antenna can break through the theoretical limitations of traditional ESA, and bring great opportunities for developing the miniaturization design of traditional antenna, and it is of great significance to promote the development of wireless communication technology. However, the low radiation efficiency of piezoelectric antenna limits its application in wireless communication, which is also an important challenge to the application of piezoelectric antenna. At present, we are also actively exploring some methods to improve the radiation efficiency of piezoelectric antenna, such as array design of piezoelectric antenna, piezoelectric metamaterial antenna, modulation technology of piezoelectric antenna and seeking for high-performance piezoelectric materials.

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