Ultra-Wideband Electrostrictive Mechanical Antenna

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Mechanical antennas based on piezoelectric materials can effectively reduce the size of long wave antennas down to 1/1000 of the wavelength (from km scale to mm level). However, the narrow bandwidth and weak field intensity seriously restrict its practical applications in transmission distance and channel capacity. Here, a mechanical antenna-based electrostrictive effect of relaxor ferroelectric ceramic (PMN-PT) is proposed to improve radiation capacity and achieve ultra-wideband characteristics (10 kHz–1 MHz). Due to the ultra-high dielectric constant at working temperature and the relationship between the strain and applied field intensity, the proposed antenna gets rid of the dependence on the poled materials and exhibits excellent communication properties beyond traditional mechanical antennas, which are experimentally demonstrated by a practical wireless communication system. Only using a single proposed mechanical antenna with 8 mm diameter and 3 mm thickness, the effective communication with a transmission distance of 200 m can be realized. This design offers a promising way of constructing mechanical antennas for long-wave communication.

1. Introduction

Recently, there has been growing interest in the research about portable very low frequency (VLF, 3–30 kHz) antenna devices. Compared with high frequency (3–30 MHz) antenna, VLF antenna exhibits relatively low propagation loss and stronger penetration of seawater and dirt, thus facilitating remote communication, military communications, geological exploration, etc.[1,2] Generally, a resonant antenna can achieve better radiation effects only when its size is close to the operating wavelength. Therefore, currently available VLF antennas typically cover an area of more than hundreds of square kilometers. An electrically small antenna is a miniaturized antenna device that has been proven feasible, and can greatly reduce the size of the antenna to less than 1/10 of the operating wavelength.[3] However, the minimum radiation quality factor of an electrically small antenna is limited by its size according to the Chu limit,[4] and these antennas generally have narrow bandwidth due to the large reactance. Various shapes, high-dielectric materials, metamaterials, and lumped components have been employed for improving antenna bandwidth and radiation resistance, but the results are far from satisfactory.[5,6] Moreover, even the electrically small antennas in the VLF band have a large physical size because of the necessity of an additional impedance-matching network, which is not beneficial for practical applications in long-wave communication.

A mechanically based antenna is an antenna design concept proposed in recent years.[7,8] Conventional electrically small antennas rely on oscillating charges to radiate electromagnetic (EM) waves, while mechanical antennas are driven by acoustic self-resonance to generate the mechanical motion of charge or magnetic dipole moment oscillations, which results in the EM waves generation.[9] Since its self-resonance at acoustic wavelength, mechanical antennas can eliminate the need for a bulky, external impedance-matching network. Furthermore, its physical size can be greatly reduced to less than 1/1000 of the operating wavelength. According to the latest reports, piezoelectric materials, such as quartz, single-crystal lithium niobate (LN), and lead zirconate titanate (PZT), have been successfully used to generate acoustic resonance for radiating EM waves in the VLF band.[10] However, mechanical antennas based on piezoelectric materials usually have a narrow bandwidth due to the inverse piezoelectric effect.[11–13] For example, an LN piezoelectric electric dipole presented for
high radiation efficiency can only operate near 35.5 kHz.\[^{[14]}\]
Actually, in civil and military applications, wideband has been urgently demanded in communication, radar, imaging, and positioning, since it means high data rate, strong anti-jamming capabilities, concealed transmission, etc. Apparently, mechanical antennas based on piezoelectric materials are not suitable for these applications. Moreover, piezoelectricity depends on the asymmetry of lattice and it is directly affected by the switching of ferroelectric domains. Consequently, the variation in temperature and stress will significantly affect the antenna’s performance. During a long-term operation, a piezoelectric resonator will generate a lot of heat and inhomogeneous stress fields due to internal friction, especially when operating near the resonant frequency \(f_r\). In conclusion, the mechanical antenna based on piezoelectric materials is an important achievement in the process of antenna miniaturization and has a certain practical value, but it has some limitations in a working environment.

For expanding bandwidth and broadening applicable scenes, a new strategy was proposed in this work from the perspective of material design. Electrostrictive effect is an electro-mechanical coupling effect, which can generate electric field-induced strain like the inverse piezoelectric effect. The difference is that the electrostrictive effect can also occur in symmetric crystals, thus it is insensitive to the phase transition and the electrical dipole switching caused by temperature and stress variation.\[^{[15,16]}\] 2.5Sm-PMN-29PT is a relaxor ferroelectric material with a low Curie temperature \(T_C\), high piezoelectric constant, and ultra-high electromechanical coupling coefficient. Therefore, a relaxor ferroelectric ceramic 2.5Sm-PMN-29PT was selected to fabricate a cylindrical resonator, expecting to radiate EM waves under a periodic electric field. In this work, it was found that this resonator keeps working above \(T_C\) under the excitation of high-frequency electric field and radiates EM waves by electrostrictive effect rather than inverse piezoelectric effect. In addition, different from the PZT or LN mechanical antennas, 2.5Sm-PMN-29PT mechanical antenna presents an ultra-wideband and stronger radiation intensity. Finally, the feasibility of this mechanical antenna for communication was verified by demonstrations of signal modulation, transmission, and receiving within an ultra-band. It is believed that the characteristics of ultra-band and high radiation efficiency of this mechanical antenna would accelerate its practical implementation process in long-wave communication.

2. Results and Discussion

Inverse piezoelectric effect results from the linear electromechanical interaction between the mechanical and electrical states in crystalline materials with no inversion symmetry. As shown in Figure 1a, the material has a spontaneous polarization \(P_s\) due to the asymmetric crystal structure. Under the action of a polarization electric field \(E_{pol}\), \(P_s\) reorientates toward the \(E_{pol}\), accompanied by the switching of the ferroelectric domains. After the polarization electric field is removed, the material still retains a remnant polarization \(P_r\). Then, under the excitation of an external AC electric field, the material will extend and contract alternately, yielding positive and negative strains.\[^{[17]}\] Electrostriction is a fourth-rank polar tensor, thus presenting in all crystal symmetries. Electrostriction is a measure of the polarization induced by ions shifting away from their natural equilibrium positions, giving rise to variations in the lattice parameters (strain). In centrosymmetric crystals, the induced shifts of equivalent ions almost cancel each other out, while the difference in the shifts because of potential anharmonicity generates strain. Based on the potential characteristics, the relative displacement between positive and negative ions (polarization) is prone to occur via the extension of the lattice instead of compression, as illustrated in Figure 1b. In consequence, the

![Figure 1](https://www.advancedsciencenews.com)

Figure 1. Mechanism analysis. Simplified illustration of a) inverse piezoelectric effect and b) electrostrictive effect.
longitudinal electrostrictive coefficient $Q_{33}$ is generally positive for ionic crystals.\[16\]

For a perovskite ferroelectric thick disk working in thickness vibration mode, the strain $S_E$ caused by the electrostrictive effect and the polarization intensity $P$ can be represented as:

$$ S_E = Q_{33}P^2 = Q_{33}e_0e_rE^2 $$

(1)

where $Q_{33}$ is the electrostriction coefficient, $E$ is the applied electric field, $e_0$ and $e_r$ are relative dielectric constant and dielectric constant of vacuum, respectively.

While the strain $S_P$ derived from the inverse piezoelectric effect can be formulated as:

$$ S_P = dE = (2P_dQ_Ee_0)e_r $$

(2)

where $d$ is the piezoelectric coefficient. It can be seen from Equation 1 and 2 that both $S_E$ and $S_P$ are related to $e_r$ and $Q$ of the material, and $S_E$ is proportional to the second power of $e_r$, while $S_P$ is proportional to the first power of $e_r$.

Generally, the total electrostrains of ferroelectric materials below their Curie temperature are composed of $S_E$ and $S_P$. At this stage, the $S_E$ is usually much smaller than the $S_P$, so the contribution of $S_E$ is often neglected. It is known that piezoelectric materials will inevitably produce an enormous amount of heat due to internal friction during operation, so their temperature will rise with external input power and working time.\[18\] When the temperature rises close to the Curie temperature, the contribution of $S_P$ decreases with the improvement of crystal symmetry, while the contribution of $S_E$ increases with the enhancement of $e_r$. Until the temperature exceeds the Curie temperature, where the material transforms from ferroelectric-phase to paraelectric-phase, the inverse piezoelectric effect disappears, and the electrostrictive effect contributes all the electrostrictive strain.

Relaxor ferroelectric materials are a kind of ferroelectric materials with diffused phase transition and frequency dispersion. Uchino proposed its “relaxor” characteristics come from the disordered perovskite crystal structure.\[15\] Different from the scenario in typical ferroelectrics, the dielectric constant of relaxor ferroelectrics reaches a plateau near the ferro-paraelectric phase transition temperature, so a large hysteresis-free electrostrictive strain can be obtained. Based on the above analysis, we expect to apply the electrostrictive effect of relaxor ferroelectrics to fabricate the mechanical antennas by tailoring the electrical performance. The ideal relaxor ferroelectric material applied in our design should have a large $e_r$ during operation, ensuring a strong electrostrictive effect. Although, the working temperature does not directly affect the electrostrictive effect of the ferroelectric material. The dielectric constant of the material will vary with working temperature, thus affecting the electrostrictive effect. Therefore, the temperature-dependent dielectric constant of 2.5Sm-PMN-29PT ceramic is shown in Figure 2a, which presents a typical diffused phase transition and frequency dispersion of $e_r$. Its ferro-paraelectric phase transition temperature is $\approx 90 ^{\circ}$C, and the $e_r$ at this temperature range reaches up to 20000–35000, which is beneficial for enhancing the electrostrictive effect. The polarization-electric field ($P$-$E$) loop and the strain-electric field ($S$-$E$) curve of 2.5Sm-PMN-29PT ceramic were measured at 25 and 110 $^{\circ}$C under 2 kV mm$^{-1}$, and

**Figure 2.** Characterization of the ceramic material. a) Temperature dependence of dielectric permittivity $e_r$ of 2.5Sm-PMN-29PT ceramic. Polarization-electric field ($P$-$E$) loop and strain-electric field ($S$-$E$) curve of 2.5Sm-PMN-29PT ceramic measured at b) 25 $^{\circ}$C and c) 110 $^{\circ}$C under 2 kV mm$^{-1}$. d) Received wireless spectrum of 2.5Sm-PMN-29PT ceramic mechanical antenna at different test cycles in the ranges of 10–500 kHz.
the corresponding results were displayed in Figure 2b,c, respectively. As can be seen in Figure 2b, 2.5Sm-PMN-29PT ceramic shows strong piezoelectric properties at 25 °C, with the typical positive and negative strains of piezoelectric materials. Above the Curie temperature, its piezoelectricity basically disappears, and there is only positive strain due to the electrostrictive effect.

Based on the conclusions above, 2.5Sm-PMN-29PT ceramic is a potential material for electrostrictive mechanical antenna. In order to verify the working temperature in the operation as a mechanical antenna, a poled 2.5Sm-PMN-29PT ceramic as the resonator was subjected to 10 cycles of frequency sweep test under the driving electric field of 10–500 kHz. The received radiation signal power is shown in Figure 2d. The specific process of the experiment implementation was elaborated in detail in the Supporting Information. In the 1st cycle, it is found that the received peak power has a radiation peak similar to the piezoelectric antenna at 150 kHz, and then the peak gradually disappears and the intensity increases significantly with frequency. Eventually, at the 10th cycle of measurement, the radiation intensity exhibits stable broad-band received power without radiation peak. It should be noted that the wireless spectrum of 1st cycle shown in Figure 2d not only exhibits the received energy of the loop antenna at different frequencies, but also illustrates the process of time and heat accumulation. During this process, the temperature of the proposed antenna increases until it reaches balance. Thus, it also is a variation process of dielectric permittivity as shown in Figure 2a. The peak value of 1st cycle corresponds to the received power when the proposed antenna is at Curie temperature. In material fabrication, it is impossible to accurately control materials operating temperature at Curie temperature. Besides, the ultra-wideband characteristic arises from the electrostrictive effect which requires the operating temperature beyond Curie temperature. Synthesizes the above factors, we do not pursue the peak value of 1st cycle.

According to the analysis in the Supporting Information, the narrow band of mechanical antenna based on piezoelectric effect is related to the material’s resonance property. The poled 2.5Sm-PMN-29PT ceramic below Curie temperature has the same resonance property as the piezoelectric resonator, showing the minimum impedance and maximum strain at $f_s$. Reflected in the generation of EM waves, it is a peak of received radiation intensity. Due to the accumulation of heat, the temperature of poled 2.5Sm-PMN-29PT ceramic exceeds its Curie temperature at the point indicated by the blue arrow in Figure 2d, thus the material depolarizes rapidly. To verify the depolarization phenomenon of the poled 2.5Sm-PMN-29PT ceramic during the experiment, we measured the piezoelectric coefficient $d_{33}$ value of 2.5Sm-PMN-29PT ceramic with different sizes before and after testing, as shown in Table 1. The results show that $d_{33}$ value of all 2.5Sm-PMN-29PT ceramic thick disks with different thicknesses drop to zero after the test. Therefore, it is proved that the working temperature of 2.5Sm-PMN-29PT ceramic is above its Curie temperature (90 °C). For further nailing down its working temperature range, a variable temperature electromagnetic radiation experiment was designed (Figure S1, Supporting Information). Through this experiment, the working temperature (90–110 °C) of 2.5Sm-PMN-29PT ceramic is definitely beyond its Curie temperature. Therefore, the mechanism of 2.5Sm-PMN-29PT ceramic is based on electrostrictive effect under working conditions, but not inverse piezoelectric effect or their coexistence. The operating mode of dielectric resonance and the influence of electrodes are further analyzed in Supporting Information to clarify the real working mechanism of the proposed antenna (Figure S2, Supporting Information).

A 2.5Sm-PMN-29PT ceramic thick disk with a thickness of 3 mm and a diameter of 8 mm, as shown in the inserted illustration of Figure 2a, is selected as the cylindrical resonator of the proposed mechanical antenna. The thickness vibration mode of 2.5Sm-PMN-29PT under the action of periodic AC electric field is utilized to excite EM waves. The cylindrical resonator works above the Curie temperature consistently due to its thermal effect during work, avoiding the influence of the inverse piezoelectric effect. 2.5Sm-PMN-29PT ceramics were prepared by solid-state sintering, the detailed process can be found in Experimental Section. A typical perovskite phase was determined using a high-resolution X-ray diffractometer with Cu Kα radiation (Figure S3, Supporting Information). The characteristic diffraction peaks indicate a rhombohedral phase structure, which corresponds with the previous work. The SEM result (Figure 3a) shows that 2.5Sm-PMN-29PT ceramic possesses a dense microstructure with an average grain size between 5–8 µm. The distributions of elements were examined by using field-emission scanning electron microscopy (Figure S4, Supporting Information). All elements are homogeneously distributed, and no element enrichment is observed. A classical disordered slush-like domain morphology was observed from the PFM result (Figure 3b), reflecting its significant relaxor ferroelectric property.

The electrostrictive effect of 2.5Sm-PMN-29PT ceramic is believed the main physical mechanism of its use as a cylindrical resonator in this study. Because of its different physical mechanism, the proposed mechanical antenna has great potential to show excellent performances in terms of bandwidth, radiation intensity, and easy fabrication. The detailed transmission characteristics will be exhibited in the following passages to verify its electromagnetic properties.

For the frequencies below 10 kHz, the pink noise is stronger than the signal intensity and is greatly influenced by temperature. Thus, the performance of the mechanical antenna in the frequency range of less than 10 kHz is not to be considered. Using the max hold function and segmental measurement method, the continuous peak power curve in the range of 10 kHz–1 MHz was measured. The detailed connection schematic of the measurement system is shown in Figure 4a. For the clear exhibition, the measured wireless spectrums with different feeding frequencies equally distributed in all the bands were shown as examples. For instance, the black curve in

| No. | Diameter [mm] | Thickness [mm] | $d_{33}$ before testing [pC/N] | $d_{33}$ after testing [pC/N] |
|-----|--------------|----------------|-------------------------------|-----------------------------|
| 1   | 8.03         | 3              | 1120                          | 0                           |
| 2   | 8.12         | 5              | 985                           | 0                           |
| 3   | 8.10         | 8              | 870                           | 0                           |
Figure 4b represents the received spectrum while the proposed mechanical antenna is stimulated by 20 kHz feed signals and radiates EM waves with the same frequency. At low frequencies, the mechanical antenna acts like a capacitor, and the radiation intensity increases with operating frequency. In the range of 50–550 kHz, the received peak power reaches and stays beyond –40 dBm (Figure 4c), which is different from the traditional piezoelectric mechanical antennas with a narrow resonant peak near the acoustic resonant frequency. In the higher frequency band of 550 kHz–1 MHz, the received power maintains a high level and shows a slight decrement trend (Figure 4d). In these bands, the measured wireless spectrum (Figure 4e) of the proposed mechanical antenna obtains peak power beyond –70 dBm, which can be obviously distinguished from the environmental noises. These bands thus can be used as operating frequency bands in communication systems. The measurement range is limited by the bandwidth (20 Hz–1 MHz) of receiving antenna used in our experiment. As expected from the trend of the measured wireless spectrum curve shown in Figure 4e, the operating frequencies include a higher frequency band.

It is known that the electric performance of a piezoelectric resonator under an AC electric field is equivalent to an RLC resonant circuit. It has the smallest resistance at a specific frequency (i.e., resonant frequency \( f_r \)), thus exhibiting maximum field-induced strain and polarization intensity near this frequency. Reflected in the radiation performance, the antenna only achieves impedance matching at its resonant frequency. It means the resonator only can effectively radiate EM waves near the resonant frequency, leading to the narrow bandwidth of conventional piezoelectric mechanical antennas. In our design, because of the lower Curie temperature, 2.5Sm-PMN-29PT will rapidly depolarize during operation and it is equivalent to a capacitor for the applied load circuit at this time. Its equivalent impedance gradually approaches zero with the increasing frequency under AC electric field. This impedance curve of an unpoled material shows a broad and flat trend in the high-frequency band (Figure S5, Supporting Information). Therefore, the 2.5Sm-PMN-29PT resonator can achieve high field-induced strain in a wide frequency range of the applied electric field. For the performance of the antenna, it can achieve ultra-bandwidth characteristics.

Equation 1 and 2 indicate that \( S_P \) is proportional to the first power of the dielectric constant, but \( S_E \) is proportional to the second power of the dielectric constant. In the same conditions, resonators based on the electrostrictive effect can get higher strain than the one caused by the inverse piezoelectric effect. Due to the second power relationship, on one hand, high strain can result in strong radiation for mechanical antenna, on the other hand, electric field inversion will not change the direction of strain. These characteristics bring advantages for the resonator in radiation enhancement, hysteresis free, and good repetitiveness. Moreover, it is also attributed to the huge difference in their dielectric constants at their respective operating temperatures (see Supporting Information). Therefore, the proposed mechanical antenna obtains higher radiation capacity.
According to the depolarization phenomenon, it is ulteriorly illustrated that the resonator made with unpoled materials can directly achieve the same efficiency, which will simplify the fabrication process and save energy.

To verify the above statement on the polarization, the proposed mechanical antenna with poled material was also fabricated, and the relative measurements were also performed. It should be mentioned that all 2.5Sm-PMN-29PT ceramics used in the proposed mechanical antenna have the same parameters in composition and preparation process except for polarization. In this condition, the measured results (Figure S6, Supporting Information) of the received wireless spectrum and peak power curve show consistency with the unpoled prototype. As well as the same trend and amplitude, this mechanical antenna also exhibits ultra-wideband characteristics. These performances demonstrate that the EM radiations of these mechanical antennas are the same. Therefore, the mechanical antenna with unpoled material is directly used in our design, which is beneficial for saving costs.

Signal modulation is a crucial part of practical communication systems. In our experimental system, a lock-in amplifier (LIA) is employed to measure the received signals under a normal noise environment. Here, an amplitude shift keying (ASK) modulation scheme is used in signal processes. The frequency of input signals is modulated and amplified by an arbitrary function generator (AFG) and a power amplifier, respectively. By setting the repeat times and waveform sequence, 50% of duty cycle ASK signals are generated (Figure 5a). In this case, the frequency of the carrier signals is limited by the operating frequency band of the proposed mechanical antenna, and the information transmission rate is determined by the source signals’ cycle that is associated with the sampling rate of the AFG and the responding rate of the LIA. The generated feed signals are directly applied to the electrodes of the electrostrictive

Figure 4. Bandwidth measurements. a) Connection schematic of the measurement system. Received wireless spectrum of the proposed antenna in the ranges of b) 10–90 kHz, c) 50–550 kHz, and d) 550–1050 kHz. e) Peak power curve. Here the measurement distance is set to 80 cm.
mechanical antenna without any external circuit. In the receiving terminal, the LIA with the same reference frequency as the carrier signals measures the amplitude, components, and phase of the received signals (Figure 5b). Because of the 50% duty ratio of the source signals, the received signals show a square waveform that represents a series of binary information. The relatively constant amplitude illustrates the stability of information transmission and low error rate. Here, low-frequency source signals are given as a sample to exhibit the information transmission. In fact, this frequency can be set to other values and even be the same as the carrier signals if the response rate of the receiving terminal is fast enough (Figure S7, Supporting Information). In addition, the 2.5Sm-PMN-29PT used in the proposed antenna has a large electrostrictive coefficient and almost no lag. In the operating band (at least in the range of 10 kHz–1 MHz), the proposed antenna can successfully radiate EM waves at any frequency. All these measured results demonstrate the feasibility of the proposed electrostrictive mechanical antenna in long-wave communication systems.

Because of the weak radiation field intensity, the realization of remote transmission remains extremely challenging in current mechanical antenna design. To demonstrate the ultra-wideband performance and remote transmission capacity of the proposed mechanical antenna, a wireless communication system is designed (Figure S8, Supporting Information). In low-frequency communications, a magnetic loop antenna is often used as the receiver to measure the magnetic field intensity. Therefore, a loop antenna connected with an LIA is employed to measure the field intensity of the EM waves transmitted from the mechanical antenna in our experiment system. With this communication system, the capability of the proposed mechanical antennas in transmission distance is evaluated (Figure 5c). According to the equivalent model of the dipole current, the magnetic field intensity follows an inverse square
relation with the distance between the transmitting antenna and the receiver. Great attenuation occurs in the vicinity near the transmitter, while the attenuation in the far-field is close to zero. The transmission distance experiments operating at 20, 200, and 700 kHz are individually performed. Compared with low-frequency bands, the signals at higher frequencies have lower environmental noise in the free space. At the frequency of 20 kHz, the mechanical antenna acts like a capacitor and works in a big noise environment. Therefore, the proposed antenna operating at 200 kHz and 700 kHz has greater radiation intensity. These trends are consistent with the measured spectra (Figure 4e).

Using the above ASK modulation at the operating frequency of 700 kHz, the different binary information of repeated “110” is transmitted to examine the ability of coding and decoding (Figure 5d). According to the identification degree of the decoded signals, it can be found that the mechanical antenna can realize effective communication within a distance of 200 m under our experimental conditions. Moreover, the magnetic field intensity at a distance of 200 m can reach 0.34 pT. Aid by highly precise devices and signal processes, the transmission distance can be further increased. Based on the relationship between the magnetic field intensity and transmission distance, a fitting equation is employed to predict the magnetic field intensity at greater distances. The fitting equation can be described as\( I = A/x^n \), where \( x \) represents the transmission distance, \( A \) is the fitting parameter. Take the measured data at 700 kHz as an example, the predicted magnetic flux density at 1 km is 23 fT, which is an efficient measure intensity for modern wireless communications (Figure S9, Supporting Information). These results verify the characteristics of the proposed electrostrictive mechanical antenna in ultra-wideband and remote transmission, which provides the hardware base for long-wave communication.

3. Conclusion

We have designed an electrostrictive mechanical antenna with the prominent features of compact size, ultra-wide operating band, and high radiation intensity. Unlike traditional mechanical antennas which are based on the inverse piezoelectric effect, the proposed mechanical antenna is mainly derived from the electrostrictive effect and uses unpoled materials. Moreover, a wireless communication system was established to verify the practical performance of the proposed antenna in coding, transmitting, receiving, and decoding. Our experiment system successfully realized wireless communication at a distance of 200 m. Besides, the fitting equation of magnetic field intensity predicts the remote transmission ability (beyond 1 km) of the proposed mechanical antenna. Our design will contribute to the development of long-wave antennas that may greatly reduce the volume of VLF communication systems.

4. Experimental Section

**Materials Preparation:** \( \text{Pb}_0.9625\text{Sm}_{0.025}(\text{Mg}_{1/3}\text{Nb}_{2/3})_{0.71}\text{Ti}_{0.29}\text{O}_3 \) (2.55m-PMN-29PT) ceramics were fabricated by using the conventional solid-state reaction method. First, the \( \text{MgNb}_2\text{O}_5 \) powders were prepared at 1000 °C for 6 h by using raw materials \( \text{MgO} \) (99.9%) and \( \text{Nb}_2\text{O}_5 \) (99.9%). Then, the \( \text{Pb}_2\text{O}_4 \) (99%), \( \text{MgNb}_2\text{O}_5 \), \( \text{TiO}_2 \) (98%), and \( \text{Sm}_2\text{O}_3 \) (99.5%) powders were mixed by the planetary ball milling in ethanol for 24 h. The mixture was dried and calcined at 800 °C for 2 h and the synthesized powder was subjected to another round of ball milling. Before being pressed into pellets of 10 mm in diameter and 3.5 mm in thickness under 60 MPa, the obtained slurry was dried and mixed with an appropriate amount of PVA binder. Later, the PVA binder was burnout at 550 °C for 6 h. Finally, the green pellets were sintered in an alumina crucible at a temperature of 1200 °C for 3 h, and buried in sacrificial powder. Due to the volume shrinkage during the sintering process, the diameter of the ceramic sheet obtained after sintering is ~8 mm, and the thickness is ~3.2 mm. Both surfaces of the ceramic samples were polished to 3 mm and painted with silver paste, and then fired at 600 °C for 30 min to form electrodes. Ceramic samples were poled at 25 °C in a silicone oil bath with an applied electric field of 1.5 kV mm\(^{-1}\) for 30 min.

**Material Characterization:** The phase structure of ceramic samples was determined by using a high-resolution X-ray diffractometer (XRD, D/max-2500 V; Rigaku, Japan) with Cu Kα radiation. The surface morphology of ceramic samples was examined by using field-emission scanning electron microscopy (FE-SEM, Merlin VP compact Zeiss, Germany). A atomic force microscope (MFP-3D, Asylum Research, USA) with the piezoresponse force microscopy (PFM) module was used to investigate the local ferroelectric/piezoelectric behavior of ceramic samples. The quasi-static piezoelectric coefficient \( d_{33} \) was measured using a Berlincourt meter (Z-3A, Institute of Acoustics, Chinese Academy of Science, China). Polarization and strain \( S(E) \) hysteresis loops were measured by using a ferroelectric tester (aixACCT TF Analyzer 2000, Germany). Temperature-dependent permittivity and dielectric loss were measured by using an impedance analyzer (TH2827, Zhangzhou Tonghui Electronic Co, China), which is coupled with a temperature-regulated sample chamber. An impedance analyzer (E4990A, Keysight, USA) was utilized for measuring impedance.

**Modulation Measurement:** In the experiment system (Figure 5b, Supporting Information), a proposed mechanical antenna and a magnetic loop antenna (SAS-565L, A.H. Systems) were used as transmitters and receivers, respectively. The mechanical antenna was driven by 20 kHz/200 kHz/700 kHz signals input directly from a power amplifier (ATA-4052, Aigtek) which was connected to an AFG (AFG 31 000 Series, Tektronix). The ASK modulation was performed by the control of the AFG with a peak voltage of 2.5 V. The signals from the AFG will obtain 100 times gain by using the power amplifier. However, the actual input voltage is determined by the load (mechanical antenna) and limited by the overload protection of the power amplifier. In receiving terminal, an LIA (SR865A, Stanford Research Systems) with the same reference frequency as feed signals was implemented to extract the signals from an extremely noisy environment. Limited by the measurement precision of the LIA, the periodic source signals should not be too small. For spectrum measurements, the LIA was replaced with a spectrum analyzer (N9320B, Keysight) in the experiment system.

**Radiation Power and Efficiency Measurement:** With the help of a current probe, oscilloscope, and spectrum analyzer, the input voltage, input current, and received power were directly measured in the experiment system (Figure 5b, Supporting Information). The input power and radiation power can be further calculated by these measured data, thus obtaining the efficiency of the proposed mechanical antenna. Due to the ultra bandwidth, the operating conditions at 20, 200, and 700 kHz were measured to provide samples for exhibiting the radiation capacity of the proposed antenna. The measured results are shown in Table 2. It is noteworthy that the received power measured by the loop antenna is the component of electromagnetic wave at one point in free space.

| Fre. [kHz] | Voltage [Vpp] | Current [App] | Input power [W] | Received power [W] | Efficiency |
|-----------|--------------|--------------|-----------------|-------------------|------------|
| 20        | 402          | 1.39         | 279.39          | 7.39 × 10^{-6}    | 2.70 × 10^{-6}      |
| 200       | 354          | 5.20         | 159.30          | 5.81 × 10^{-5}    | 3.65 × 10^{-7}     |
| 700       | 41.4         | 5.06         | 104.74          | 5.93 × 10^{-5}    | 5.66 × 10^{-7}     |

Table 2. Measured electrical parameters and calculated results of the proposed antenna.
space. The loop antenna was put near the radiation antenna to represent radiation power with received power. And there is no amplifier circuit in the received terminal. Therefore, the radiation power, in fact, is greater than the received power and the efficiency is higher than the calculated value in Table 2. According to the measured results shown in Table 2, the estimated radiation efficiency of the proposed antenna is between $2.70 \times 10^{-8}$ and $5.66 \times 10^{-7}$. And the real radiation efficiency is at least 2 – 3 times higher than the radiation efficiency of previous work (between $1 \times 10^{-8}$ and $2 \times 10^{-7}$).\[54] In addition, the received powers in xoy plane with a distance of 3 m were measured to form the radiation pattern of the proposed mechanical antenna (Figure S10, Supporting Information). From the measured results, the radiation patterns in xoy plane at 20, 200, and 700 kHz all exhibit omni-directivity. These radiation patterns are well coincident with the radiation characteristic of a dipole antenna, thus illustrating the operating mechanism of the proposed antenna.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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electrostriction, mechanical antenna, ultra-wideband antenna

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