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Directional Transmission of Ultra-high Frequency Acoustic Signals Based on Metamaterial Structure

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Directional transmission of ultra-high frequency acoustic signals based on metamaterial structure

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ABSTRACT
Cell photoacoustic detection of acoustic signals has serious problems of transmission loss and difficulty in acquisition. Based on the acoustic transmission characteristics of acoustic supermaterials, the acoustic wave directional transmission model is designed using COMSOL software, and a finite element simulation experiment was carried out. Experiments show that the model designed in this paper has good sound wave focusing and acoustic wave directional transmission effects. According to the specific application in different environments, this paper designs a variety of transmission models with different structures and carries out comparative experiments to verify the influence of complex model structures on the directional transmission of sound waves. At the same time, the experimental analysis of the acoustic wave directional transmission effect of the model under different frequency segments is carried out, and the possibility of acoustic wave logic operation is verified. Models can be applied to high frequency acoustic signal acquisition and sound wave transmission in complex environments. These studies have important significance for the development of cell photoacoustic detection technology and the application of metamaterial structures and have good practical merit.

I. INTRODUCTION
With the development of biotechnology, the realization of directed culture of cells has become one of the focuses of attention. In the process of cell culture, it is necessary to find a way to detect cells effectively. Traditional detection methods have some problems and deficiencies in the application process. Photoacoustic detection technology plays an important role in cell detection by virtue of its own characteristics.

Ultrahigh frequency (UHF) sound waves are generated during cell photoacoustic detection. Due to the limitation of the transmission characteristics of high-frequency acoustic signals, the acquisition of acoustic signals is relatively difficult. The realization of directional transmission of acoustic signals is of great significance for their collection and analysis. In this paper, aiming at the demand of acoustic signal transmission in cell photoacoustic detection, combined with the characteristics of high-frequency acoustic wave transmission, a method suitable for directional transmission of UHF acoustic signals is studied.

II. DIRECTIONAL TRANSMISSION OF ULTRAHIGH FREQUENCY ACOUSTIC SIGNALS
The acquisition of ultrahigh frequency acoustic signals is an important task in the process of cell detection. The acoustic signal has substantial loss in the transmission process, and the transmission of the ultrahigh frequency acoustic signal is particularly obvious. Realizing the directional transmission of UHF acoustic signals can effectively overcome the problem of acoustic signal
transmission attenuation and has important significance for the acquisition of acoustic signals.

A. Cell photoacoustic detection and ultrahigh frequency acoustic signals

Photoacoustic detection technology is a new type of detection method that has attracted much attention in cell detection. Under the action of a pulsed laser, the cells will generate ultrasonic waves of a specific frequency due to thermal expansion. By collecting ultrasonic information and performing the corresponding processing work, the detection of cells can be achieved. Photoacoustic detection technology is simple in application and has the advantages of noninvasiveness and high precision. Therefore, its application in cell detection has received widespread attention. For example, early detection of breast cancer and tumors can be achieved by applying photoacoustic detection techniques. In the application process, cell photoacoustic detection technology also has certain limitations.

During the photoacoustic detection process, the frequency of the sound waves emitted by the object depends on the frequency of the optical signal. The pulse laser applied for photoacoustic detection has a high frequency. Therefore, when the cell is subjected to photoacoustic detection, the generated acoustic wave frequency can reach an ultrahigh frequency. The sound wave signal will attenuate during the transmission process, and the ultrahigh frequency sound wave signal is particularly obvious. The intensity of sound waves emitted during cell photoacoustic detection is very low. After attenuation, the acoustic signal is difficult to capture. How to realize the collection of acoustic signals by cell photoacoustic detection has always been a key topic of research.

B. Directional transmission of ultrahigh frequency acoustic signals

Photoacoustic detection requires the analysis of the physiological state of cells by the acquisition of acoustic signals. Under normal conditions, the ultrasound emitted by the monomer cells will spread in all directions at the same time. The sound signal intensity is low and attenuation is large, which jointly determine the difficulty of sound wave signal acquisition, and thus, it is difficult to achieve effective collection of sound wave signals.

Overcoming the loss problem in acoustic wave transmission is the key to solving the difficulty in collecting acoustic signals. Realizing the directional transmission of sound waves can effectively solve the problems above. Acoustic directional transmission originated in the mid-18th century. In 1962, Westervelt proposed the theory of generating directional audio using the nonlinear effects of air. In recent years, with the development of related technologies, research on acoustic directional transmission has made new breakthroughs. For example, ATC Corporation of the United States has successfully developed a parametric speaker that realizes sound-directed transmission. However, for the moment, existing systems that achieve directional transmission of acoustic waves are inefficient. This is also a major problem limiting the application of directional wave transmission.

We need to design models that satisfy the requirements for high-frequency acoustic signal acquisition and acoustic transmission in complex environments.

III. METAMATERIAL STRUCTURES AND DIRECTIONAL TRANSMISSION OF ULTRAHIGH FREQUENCY ACOUSTIC SIGNALS

The directional transmission of ultrahigh frequency acoustic signals is of great significance for the development of cell photoacoustic detection. Aiming at the characteristics of acoustic signal transmission, this paper proposes the use of metamaterial structures to realize the directional transmission of UHF acoustic signals.

A. Development status of metamaterial structures

Humans have been paying attention to the regulation research of waves for a long time. People need a new material that can achieve the negative response of sound waves in order to promote the development of sound wave regulation research. James and Norris first proposed the concept of left-handed materials in 1968, laying the foundation for the development of acoustic metamaterials. In 1992, the existence of phonon bandgaps was demonstrated by Ding et al. This research has greatly promoted the application of acoustic metamaterials. The first clear concept of acoustic metamaterials was proposed in 2000; Liu et al. systematically elaborated on the above concepts by summarizing relevant research data.

After years of development, the research on acoustic metamaterials has made great breakthroughs and has been applied in some fields. However, theoretical research on acoustic metamaterials still has relatively large defects. Due to the lack of support from the corresponding theory and technology, theoretical research on acoustic metamaterials currently focuses on one-dimensional structures. Its application effect research mainly focuses on two-dimensional structures. In research, people usually use the spring structure model to explain the theory, as shown in Fig. 1.

B. Transmission characteristics of ultrahigh frequency acoustic signals

The sound waves generated by cancerous cells during photoacoustic diagnosis belong to evanescent waves. They will become evanescent waves due to total reflection when waves are incident from a dense medium to a thin medium. The amplitude of this wave is related to the vertical depth of the interface. The evanescent wave belongs to the near-field wave. When the wave equation of the incident wave is set to

$$E = E \exp[j(kt - \omega t)],$$

the wave equation of the refracted wave is

$$E = E \exp[j(kt - \omega t)].$$

![FIG. 1. Acoustic metamaterial spring model structure.](image-url)
Then, we can infer \( ki \cdot r = ki \cdot r = kx + ky + kz \). In the case of total reflection, since the incident surface is \( y = 0 \) plane, the sagittal product is

\[
k t \cdot r = kx \sin \theta + k z \cos \theta = kx + k z, \tag{3}
\]

\[
k t \cdot r = kx \sin \theta + k z \cos \theta = kx \sin \theta + j k z \Gamma = kx + j k z \Gamma.
\]

The refraction wave equation is

\[
E = E \exp \left[ j (k x + j k z \Gamma - wt) \right] = E \exp (-k z \Gamma) \exp \left[ j (k x - wt) \right]. \tag{4}
\]

When substituting Eq. (3) into the refracted wave equation of Eq. (4), we can see that the magnitude of \( E \) decreases exponentially with \( z \). The depth of penetration is

\[
d_z = \frac{1}{2k z \Gamma \sqrt{\sin^2 \theta - 1}}. \tag{5}
\]

Through the above theoretical analysis, we can find that the intensity of the evanescent wave is exponentially attenuated with the change of the distance, and the collection of the ultrahigh frequency acoustic signal generated by the cell is difficult. The main reason is the loss during the transmission of the acoustic signal and surface diffusion of the acoustic wave. Therefore, if directional transmission of sound waves can be realized, and the loss problem in the transmission process can be overcome, the development of cell photoacoustic detection can be effectively promoted.

**C. Acoustic waveguide theory in metamaterial structures**

Metamaterials can achieve directional transmission of sound waves, which has a relatively large relationship with the theory of acoustic waveguides. In an isotropic infinite elastic solid, based on the basic elastic properties of the solid, and the X, Y, Z rectangular coordinate system, the equation of motion describing the motion of the medium particle in the solid is\(^{10,11}\)

\[
\rho \frac{\partial^2 U_x}{\partial t^2} = (\lambda + \mu) \frac{\partial^2 U_x}{\partial x^2} + \mu \nabla^2 U_x, \tag{6a}
\]

\[
\rho \frac{\partial^2 U_y}{\partial t^2} = (\lambda + \mu) \frac{\partial^2 U_y}{\partial y^2} + \mu \nabla^2 U_y, \tag{6b}
\]

\[
\rho \frac{\partial^2 U_z}{\partial t^2} = (\lambda + \mu) \frac{\partial^2 U_z}{\partial z^2} + \mu \nabla^2 U_z. \tag{6c}
\]

In the middle,

\[
\Delta = \frac{\partial U}{\partial x} + \frac{\partial U}{\partial y} + \frac{\partial U}{\partial z},
\]

\[
\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}.
\]

\( U_x, U_y, \) and \( U_z \), respectively, represent the displacement vectors of a mass point in the solid in the X, Y, and Z directions, and \( \lambda \) and \( \mu \) are the pull density (\( \mu \) can be called the shear elastic coefficient), which is the density of the solid medium.

By introducing a scalar potential function and a vector potential function, Eq. (6) can be expressed as two independent equations:

\[
\rho \frac{\partial^2 \phi}{\partial t^2} = (\lambda + 2 \mu) \nabla^2 \phi, \tag{7}
\]

The potential function can be represented by its component,

\[
\rho \frac{\partial^2 \psi_i}{\partial t^2} = \mu \nabla^2 \psi_i \quad (i = X, Y, Z). \tag{9}
\]

The velocity of the medium’s particle in all directions can be determined from the potential function,

\[
V_x = \frac{\partial U_x}{\partial t} = \frac{\partial \phi}{\partial x} + \frac{\partial \psi_x}{\partial x} = \frac{\partial \psi_y}{\partial y} + \frac{\partial \psi_z}{\partial z}, \tag{10a}
\]

\[
V_y = \frac{\partial U_y}{\partial t} = \frac{\partial \phi}{\partial y} + \frac{\partial \psi_x}{\partial y} + \frac{\partial \psi_z}{\partial z}, \tag{10b}
\]

\[
V_z = \frac{\partial U_z}{\partial t} = \frac{\partial \phi}{\partial z} + \frac{\partial \psi_x}{\partial z} + \frac{\partial \psi_y}{\partial y}. \tag{10c}
\]

From Eq. (7), in the medium \( \psi = 0 \), the direction of propagation of the wave is X, and \( \phi = 0 \), and \( \psi_x = \psi_y = 0 \). It can be obtained from Eq. (10) that

\[
V_x = \sqrt{\frac{\lambda}{\rho}} \psi_x = \sqrt{\frac{\lambda}{\rho}} e^{j(\omega t - k_x x)}, \tag{11}
\]

\[
V_y = \sqrt{\frac{\lambda}{\rho}} \psi_y = 0.
\]

It describes the law of longitudinal waveform Eq. (11). In the middle, \( K_L = \frac{\pi}{\rho} \), where \( C \) is the longitudinal wave propagation speed, \( C_L = \sqrt{\frac{\lambda + 2 \mu}{\rho}} \) is constant, and \( w \) is the angular frequency of sound waves.

It can be obtained from Eq. (8) that the wave propagation direction is still X and \( \phi = 0 \) and \( \psi_x = \psi_y = 0 \). It can be obtained from Eq. (10) that

\[
V_x = \sqrt{\frac{\lambda}{\rho}} \psi_x = 0,
\]

\[
V_y = \sqrt{\frac{\lambda}{\rho}} \psi_y = \sqrt{\frac{\lambda}{\rho}} e^{j(\omega t - k_x x)}.
\]

It describes the law of the transverse wave. It indicates that the particle velocity (Y direction) of the medium is perpendicular to the wave propagation direction X. In the middle, \( K_T = \frac{\pi}{\rho} \), where \( C_T \) is transverse wave propagation speed, \( C_T = \sqrt{\frac{\mu}{\rho}} \), and \( \psi_A \) is constant.

It can be seen that when the size of the medium is infinitely larger than the wavelength of the propagating sound wave, two types of waveforms can exist simultaneously (or one of them alone) – transverse waves and longitudinal waves; the waves’ speed of propagation depends only on the nature of the medium.

**IV. CONSTRUCTION OF THE ACOUSTIC METAMATERIAL MODEL**

In order to meet the requirements of directional transmission of ultrasonic signals, this paper designs a structural model based on the acoustic waveguide theory of metamaterial structures. The experimental model is designed based on the structural model.

**A. Construction of the acoustic metamaterial model**

The design of the metamaterial structure model first requires the analysis of the material equivalent mass parameters and resonance frequency, as shown in Fig. 2.

By analyzing the relationship between the equivalent mass parameters and the resonance frequency, combined with the
characteristics of the ultrasonic signal in photoacoustic detection, this paper adopts an epoxy-rubber-lead three-layer acoustic supermaterial design scheme, which is realized using COMSOL software, such as Fig. 3 shows.

In Fig. 3, the innermost layer of the structure is a shot-put, the design specification is a radius $R_1 = 1.3$ mm, the middle layer is rubber, and the design specification is a thickness of 0.6 mm. The outermost layer is epoxy and has a thickness of 0.3 mm. The specific specifications are shown in Table I.

After completing the design work of the metamaterial structure model, the design of the metamaterial experimental model can be completed by orderly arranging the structure model.

### B. Design of the experimental model of metamaterials

Based on the abovementioned metamaterial structure model, this paper designs a model of acoustic wave directional transmission, as shown in Fig. 4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$ (kg m$^{-3}$)</th>
<th>Velocity $c$ (m s$^{-1}$)</th>
<th>Young’s modulus $E$ (10$^{10}$ Pa)</th>
<th>Shear modulus $\mu$ (10$^{10}$ Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1 000</td>
<td>1500</td>
<td>$2.19 \times 10^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Lead core</td>
<td>11 600</td>
<td>2160</td>
<td>4.08</td>
<td>1.49</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>1 180</td>
<td>2680</td>
<td>0.435</td>
<td>0.159</td>
</tr>
<tr>
<td>Rubber</td>
<td>1 300</td>
<td>300</td>
<td>$1.175 \times 10^{-5}$</td>
<td>$4 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

By spacing the metamaterial structure model, an acoustic wave directional transmission model with a length of 4 cm and a width of 8 cm is formed. Inside the model, part of the structural model is ruled out to form a channel for acoustic transmission.
Considering the difference between the specific application environment of photoacoustic detection, the acoustic directional transmission model can be designed to different specifications, as shown in Figs. 5 and 6.

Figures 5 and 6 are acoustic wave directional transmission models of the same size as those in Fig. 4. The channel of directional transmission of sound waves can be changed by changing the order of arrangement of the metamaterial structure models inside the model. Figure 5 shows a vertical type acoustic wave directional transmission channel, and Fig. 6 shows a sound wave shunt directional transmission channel.

V. THE EXPERIMENT OF THE METAMATERIAL STRUCTURE MODEL

In order to verify whether the model designed in this paper has good acoustic directional transmission characteristics, the related experiments were carried out and the experimental data were collected and recorded.
A. Experimental analysis of the acoustic wave directional transmission model

In this paper, the acoustic wave transmission model is studied by using the acoustic wave directional transmission model shown in Fig. 4. The specific experimental method is to place a point sound source on the left side of the model acoustic wave transmission channel to emit ultrasonic waves of a specific frequency for simulating the single cells under the photoacoustic detection state and obtain the phenomenon diagram inside the model at different times, as shown in Fig. 7.

In order to observe the magnitude of acoustic energy, the acoustic pressure field is used to represent the acoustic energy in the experimental renderings. Red and blue respectively indicate the sound pressure of sound waves in different directions. The darker the color, the higher the sound pressure value and the greater the sound wave energy.

In Fig. 7, the left point source emits ultrasonic waves at a frequency of 140 kHz. Figures 7(a)–7(d) show the simulation results for the 11 μs, 28.6 μs, 39.6 μs, and 57.2 μs time points, respectively. It can be seen from Fig. 7 that there is an inconspicuous sound wave transmission around the point source. This phenomenon is consistent with the previous analysis of this paper, that is, the ultrasonic waves emitted by the point source will propagate in all directions at the same time and the sound energy is relatively small while the transmission loss is serious.

On the right side of the point source is the sonic directional transmission model designed in this paper. There is a sound pressure field formed by sound wave transmission in the channel inside the model, and there is no sound pressure field in other places. Comparing the phenomena in Figs. 7(a)–7(d), it can be found that the sound waves are only directionally transmitted along the channel. Moreover, the sound pressure value in the channel is significantly higher than that on the outside of the model.

![Image](image.png)
Therefore, this paper believes that the designed model not only has the effect of directional transmission of sound waves but also has an obvious sound wave focusing effect. By applying this model, the ultrasonic waves generated in the photoacoustic detection of cells can be directionally transmitted to the vicinity of the signal acquisition system, which overcomes the difficulty of application of photoacoustic detection technology.

B. Acoustic directional transmission model expansion experiment

Considering the complex environment of cell photoacoustic detection, a single straight channel cannot meet the detection requirements. Therefore, this paper also designed other types of sonic directional transmission channels, carried out simulation experiments, and recorded the experimental results.

1. Influence of the channel structure on directional transmission of sound waves

In this paper, the structure of the channel is adjusted. Vertically curved channels are added to the original model to verify whether the sound wave has the characteristics of curved directional transmission, as shown in Fig. 8.

The images of the acoustic directional transmission model added to the vertical curved structure at 13.2 µs, 44 µs, 81.4 µs, and 162.8 µs are shown in Figs. 8(a)–8(d). The excitation sound wave of the point source is set to 140 kHz. Through the analysis of the phenomenon map, it can be found that the sound wave transmission phenomenon of the model is similar to that of the original model. Outside the model, sound waves are more messy. Inside the model, the sound waves propagate substantially in accordance with the designed transmission channel. This result indicates that the metamaterial model designed in this paper has a good acoustic directional transmission effect.

Comparing the phenomenon diagrams in Figs. 7(b), 7(d), 8(a), and 8(d), it can be found that the acoustic channel design inside the model does not affect the sound transmission speed. However, the lengthening of the acoustic wave transmission channel would affect the occurrence time of the acoustic signal at the output of the model. Considering the loss of energy that may occur during sound wave transmission, this paper believes that the sound transmission channel design should be adopted as simple as possible if the circumstances are permitted.

In order to further study the influence of the complex channel structure on the directional transmission of sound waves, this paper draws the waveforms of the internal sound pressure of the two experimental models with time, as shown in Figs. 9 and 10.

Figure 9 shows a waveform diagram of the internal sound pressure change of the linear model. The first change in sound pressure inside the model occurred at 40 µs. The sound pressure peak is 0.25 Pa, and the appearance time is 80 µs. Figure 10 shows a waveform diagram of the internal sound pressure variation of the vertical structure. The first sound pressure fluctuation time is 10 µs, the sound pressure peak is 0.25 Pa, and the appearance time is 102 µs. The peak value of the sound pressure remains basically the same, and the appearance time becomes late.

By comparing the phenomena in Figs. 9 and 10, it can be concluded that the change of the model structure will have a certain impact on the fluctuation time of the sound pressure value inside the model and the appearance time of the sound pressure peak. The specific impact results are that the more complex the model structure, the later the sound pressure peak appears.

2. Influence of acoustic frequency on directional transmission of sound waves

During the photoacoustic detection process, the frequency of ultrasonic waves emitted by different cells will be different. Considering the application of the model in different environments, this
paper adopts the acoustic wave directional transmission model of the bifurcation structure, carries out the simulation experiment of the model at different frequencies, and records the phenomenon, as shown in Fig. 11.

Figure 11 shows a distribution diagram of the sound pressure value inside the acoustic wave directional transmission model of the bifurcated structure under different frequency acoustic waves. By analyzing Fig. 11, it can be found that the model has good acoustic directional transmission capability in a certain frequency range. In order to observe the acoustic wave transmission inside the model in detail, this paper records the model sound pressure level distribution at 270 kHz acoustic wave frequency, as shown in Fig. 12.

It can be seen from Fig. 12 that the sound pressure level of the internal channel of the model reaches 120–140 dB, and the sound pressure level is up to 20 dB in the place where the metamaterial structure is arranged. This result shows that the model has good sound wave focusing effect while having multifrequency acoustic wave directional transmission effect.

Comparing Fig. 11(a) with Fig. 11(b), it can be found that the sound pressure distribution phenomenon inside the sound wave changes more obviously when the frequency of the sound wave changes. By changing the frequency of the sound wave, the specific direction of the directional transmission of the sound wave can be changed. This discovery provides the basis for the study of sonic logic operations.

![Acoustic wave directional transmission phenomenon at different frequencies: (a) acoustic phenomenon at 270 kHz, (b) acoustic phenomenon 272 kHz, (c) acoustic phenomenon 273 kHz, and (d) acoustic phenomenon 280 kHz.](image-url)
VI. CONCLUSION

The application of photoacoustic detection technology has a profound impact on the detection and treatment of cells. Aiming at the problem of detection difficulty caused by severe acoustic wave transmission loss and uncertain sound transmission direction in the cell photoacoustic detection process, this paper analyzes the acoustic wave transmission characteristics of the metamaterial structure and designs the acoustic wave directional transmission model in this technology. The model has a good sound wave focusing effect and acoustic wave directional transmission capability. At the same time, this paper tests the effect of the acoustic directional transmission model of different structures and finds that the more complex the model structure, the more serious the acoustic energy loss. In addition, the experiment of the model under different frequency ultrasonic waves is carried out and it is verified that it has a wide frequency range. These features prove that the models can meet the requirements of acoustic signal transmission and acquisition in complex environments. The models can be used to design new underwater acoustic communication systems and cell acoustic signal acquisition systems. Meanwhile, this paper finds that the model has the ability to perform logical operations. This is very helpful in promoting the widespread application of the model.

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