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ABSTRACT
The directional transmission of high-frequency sound waves is of great significance to the development of underwater communication and cell photoacoustic detection. In order to overcome the transmission loss of high-frequency sound waves, a new high-frequency sound wave directional transmission model based on acoustic metamaterials and graphene structures has been designed. The local sound field enhancement effect and directional transmission effect of this model on high-frequency sound waves were verified through finite element analysis. Using the special case of 450 kHz sound waves, the transmission effect of high-frequency sound waves in the model was studied. The result shows that the acoustic wave directional transmission model based on acoustic metamaterials and graphene structures had good high-frequency acoustic wave directional transmission characteristics. This research has important practical value in the research of underwater communication and cell photoacoustic detection.

I. THE PROBLEM OF HIGH-FREQUENCY ACOUSTIC SIGNAL ACQUISITION
A. Necessity of high-frequency acoustic signal acquisition
Water is a great sound wave transmission medium. In recent years, the research on low-frequency underwater acoustic signal acquisition has gradually taken precedence. However, there are problems in the research of high-frequency underwater acoustic signals.

The acquisition of high-frequency underwater acoustic signals has attracted much attention in the field of medicine. Cell photoacoustic detection is an important method for the diagnosis of many diseases. In early breast cancer detection and tumor monitoring, the photoacoustic signal diagnosis technology has played an important role. The basic principle of cell photoacoustic detection is to generate a high-frequency sound wave signal under the action of a pulsed laser. The study of cell characteristics through the analysis of acoustic signals is hence realized. In the process of cell photoacoustic detection, the frequency of sound waves is so high that it can reach very high or ultrahigh frequencies. However, high-frequency signals have the disadvantages of limited transmission distance and large transmission loss, which make the process of signal acquisition and processing more difficult. If we can realize the transmission of high-frequency underwater high-frequency acoustic signals, it will be of great significance to study the photoacoustic detection characteristics of cells.

B. Directional transmission and acquisition of high-frequency acoustic signals
The main factor that makes the acquisition of high-frequency acoustic signals difficult is the large transmission loss of acoustic signals. In a normal environment, sound wave signals will propagate to the surroundings at the same time and cause severe wear and tear. If the problem of loss in sound wave transmission can be overcome, the collection efficiency of high-frequency sound wave signals can be effectively improved. The transmission loss of high-frequency sound waves can be effectively reduced when using specific materials to achieve directional transmission of sound waves.
Directional transmission of sound waves originated in the mid-18th century. Westervelt first proposed the theory of directional audio in 1962, which uses the nonlinear effects of air to generate directional audio. With the development of sound wave research and the breakthrough of related equipment research and development, the research of sound wave directional transmission is becoming more and more matured. For example, the American ATC company has successfully developed a parametric speaker to achieve directional sound transmission. However, at present, existing systems have the problem of low efficiency in directional transmission of sound waves. This is also a major problem that restricts the application of directional transmission of sound waves.

II. GRAPHENE STRUCTURES AND DIRECTIONAL TRANSMISSION OF HIGH-FREQUENCY SOUND WAVES

Graphene, which is considered to be a revolutionary material in the future, is a two-dimensional carbon nanomaterial with a hexagonal honeycomb lattice composed of carbon atoms with sp² hybrid orbitals. Graphene has important application prospects in materials science, micro-/nano-processing, energy, biomedicine, and drug delivery because of its excellent optical, electrical, and mechanical properties. At present, graphene has also been widely used in the field of acoustics. Among them, the research on the sound absorption performance of graphene is of most concern. By analyzing the research of Bunch and others, Li established a composite structure with graphene and designed an efficient sound-absorbing tile.

Li discovered that graphene has a good ability to transmit high-frequency sound waves with low loss. However, graphene can only have this ability when the acoustic frequency reaches above THz. In cell photoacoustic detection, it is rarely possible to reach frequencies above GHz. According to the analysis and research results, this paper believes that the structure of graphene has special transmission properties for sound waves. However, its material characteristics do not meet the lossless transmission requirements of kHz–MHz acoustic waves.

Acoustic metamaterials have decent sound wave transmission characteristics and also have good results between kHz and MHz frequencies. In this paper, graphene structures and acoustic metamaterials are shown to achieve efficient directional transmission of acoustic waves at frequencies from kHz to MHz.

III. DESIGN OF GRAPHENE STRUCTURAL MODEL BASED ON ACOUSTIC METAMATERIALS

The study of acoustic metamaterials is one of the key contents of acoustic research in recent years, which also has a major
impact on the research of high-frequency acoustic wave transmission. Based on acoustic metamaterials and combining the characteristics of graphene structures, a new high-frequency acoustic wave directional transmission model is designed in this paper.

A. Development status of acoustic metamaterials

For a long time, the research on wave regulation has attracted widespread attention. In order to promote the development of acoustic wave regulation research, a novel type of material that can realize the negative parameter response of acoustic waves is needed. Therefore, Veselago first proposed the concept of left-handed materials in 1968. Subsequently, acoustic metamaterials entered a formal development phase. In 1992, Sigalas et al. demonstrated the existence of phonon band gaps. In 2000, with the first definition of acoustic metamaterials by Liu et al., the research of acoustic metamaterials entered a new stage.

At this stage, acoustic metamaterials have achieved relatively good applications in scientific research. However, the research on the theory of acoustic metamaterials is not perfect, so its practical application is restricted to a certain extent. At present, the theoretical research of acoustic metamaterials generally focuses on one-dimensional structure. The related research’s spring structure model is shown in Fig. 1.

However, compared with 2D and 3D structures, the 1D structure is difficult to achieve in practical applications.

B. Graphene structural model design and experiment

Graphene structure is a hexagonal two-dimensional structure with a honeycomb lattice. Existing research proves that graphene structures have special properties. This paper considers that this structure has special high-frequency sound wave transmission characteristics. In order to verify this view, a new acoustic structure model based on acoustic metamaterials, combining the characteristics of graphene structures, as shown in Fig. 2, has been designed.

The circular structure in Fig. 2(b) is a simplified model of the acoustic metamaterial structure. This structure can still maintain good acoustic transmission characteristics. The material parameters of each structure remain the same: metal inside and rubber outside. The structural parameters are 0.05 mm outer radius and 0.03 mm inner radius.

The acoustic metamaterial structure is arranged according to the characteristics of the graphene structure, forming a hexagonal two-dimensional structure with a honeycomb lattice. This paper designs three different paths by using graphene structures to study the directional transmission characteristics of the model. The path is made of resin, which is completely placed in a water environment. The radius of the water environment is 0.8 cm. A hard sound field

FIG. 3. Sound source location.

FIG. 4. Model sound wave transmission simulation experiment: (a) the phenomenon at 540 kHz and (b) the phenomenon of central location (frequency is 540 kHz).
FIG. 5. Model simulation effect of different frequencies: (a) the phenomenon at 477 kHz, (b) the phenomenon at 515 kHz, and (c) the phenomenon at 477 kHz.
boundary is added outside the water environment, and the overall model adds a pressure sound field.

In this paper, the sound source is set at the end of the channel of the model, and the sound pressure is 2 Pa, as shown in Fig. 3.

In this paper, the frequency-domain sound field is added to simulate the acoustic transmission characteristics of the model, as shown in Fig. 4.

The sound wave frequency in the simulation picture is 540 kHz. The red and blue parts indicate the sound pressure in different directions. The darker the color, the higher the sound pressure value. Through simulation experiments, it can be found that there are obvious acoustic wave transmission paths inside the model. The transmission is basically based on the path designed in this paper, and there is very little acoustic energy distribution outside the model. The sound pressure value inside the model increases significantly, and the peak value reaches 300 Pa, compared with the sound pressure value (2 Pa) of the sound source. This phenomenon demonstrates that acoustic metamaterials arranged in a graphene structure can still have an effect on enhancing the local sound field. Moreover, the graphene structure has a characteristic of directional transmission of high-frequency sound waves. The next simulation study is carried out to further study this characteristic.

IV. STUDY ON THE DIRECTIONAL TRANSMISSION CHARACTERISTICS OF THE GRAPHENE STRUCTURE MODEL

A. Model effect at different acoustic wave frequencies

In this paper, a frequency-domain sound field is set, and the frequency sweeping method is used to record the simulation results of the model under different sound wave frequencies, as shown in Fig. 5.

The simulation results under acoustic frequencies of 477 kHz, 505 kHz, and 520 kHz are recorded in Figs. 5(a)–5(c), respectively, where sound pressure distribution effects similar to those shown in Fig. 4 appears inside the model. The peak values of the sound pressure of the model are 40 Pa, 400 Pa, and 150 Pa, respectively, which are far higher than those of the sound source (2 Pa). This phenomenon indicates that the model has a good effect on local sound field enhancement and directional transmission on sound waves of different frequencies.

This article selects different observation points inside the model and draws the sound pressure waveform diagram of each observation point to better observe the effect of the model, as shown in Figs. 6 and 7.

Figures 7(a)–7(c) record the waveform of the sound pressure at 477 kHz, 520 kHz, and 540 kHz, respectively. It can be found that, by analyzing Fig. 7, the sound pressure change curve and the sound pressure peak basically accord with the observation results of Figs. 4 and 5. Further research found that the sound pressure peaks at different observation points are different at fixed frequencies; the sound pressure peaks of sound waves at different frequencies at the same observation point are also different. However, the peak value of the sound pressure far exceeds the sound pressure of the sound source (2 Pa), achieving a good effect on local sound field enhancement. This paper believes that this result meets the design requirements for graphene structural models.
B. Model effect at a fixed acoustic frequency

The above experiments verify the directional transmission of sound waves at different frequencies by the graphene structure model. In practical situations, directional transmission of sound waves with a fixed frequency has attracted more attention. In this paper, the 450 kHz acoustic wave is selected, and a simulation experiment is carried out under the action of the acoustic wave. The experimental parameter setting is consistent with the frequency domain simulation experiment.

Figures 8(a)–8(i) are the internal sounds of the model under the action of a 450 kHz frequency pressure distribution chart of 0 μs, 2 μs, 3.5 μs, 6.25 μs, 8 μs, 11 μs, 13.75 μs, 15.25 μs, and 16.75 μs. By analyzing Fig. 8, it can be found that when the sound source emits a fixed frequency sound wave, the sound wave will propagate along the model. When propagating to the intersection of multiple channels, the sound waves do not maintain the original propagation direction but propagate along the direction of the model.
The sound pressure value curves of the three observation points are plotted in Fig. 6 at different times to better observe the change in the sound pressure value with time in the model, and the sound pressure value curves at 0 μs, 8 μs and 16.75 μs are selected, as shown in Figs. 9 and 10.

It can be found from Fig. 9 that the sound pressure change curves of different observation points inside the model are basically similar. Therefore, this paper considers that the sound wave transmission effect at different points inside the model is very close. Observing Fig. 10(a), it can be found that the peak value of the sound pressure inside the model at the initial time is 6.5 × 10^{-6} Pa, which can be ignored. The peak sound pressure at the observation point reached 48500 Pa at 8 μs; the peak sound pressure at the observation point is 10000 Pa at 16.75 μs. This result is consistent with the changes in sound pressure values in Figs. 8(a), 8(e), and 8(i). It can improve the transmission efficiency of sound waves than the energy enhancement of the local sound field and realize the effective collection of low-energy sound waves. This has important significance in the photoacoustic detection of cells.

Simulation results show that the new model based on graphene structures has a significant directional propagation effect on high-frequency sound waves. If the sound waves are needed to propagate in other directions, we can change the direction of the model. This regulation provides a good basis for the directional transmission and acquisition of high-frequency sound waves under water.

V. CONCLUSION

The directional transmission of high-frequency sound waves is of special significance to the research of cell photoacoustic detection and the development of underwater acoustic communication. In order to overcome the problem of energy loss in the underwater transmission of high-frequency acoustic waves, a new high-frequency acoustic wave directional transmission model is designed based on acoustic metamaterials and graphene structures, and simulation experiments are performed. The experimental results show that the model has a good local sound field enhancement effect and directional transmission effect on high-frequency sound waves of different frequencies. The 450 kHz sound wave is selected as the object, and the effect of sound wave transmission at different times of the model is studied. The research results verify the model’s directional transmission of high-frequency sound waves. These studies are of great help for the development of cell photoacoustic detection and underwater acoustic communication research and the research of high-frequency acoustic wave directional transmission.

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REFERENCES

1. S. Wang, D. Zhu, and L. Chu, “Influence of the low frequency long-range underwater acoustic communication technology on submarine,” Audio Eng. 43(06), 5–7 (2019).
2. G. Ku, K. Maslov, L. Li et al., "Photoacoustic microscopy with 2-μm transverse resolution," J. Biomed. Opt. 15(2), 021302-1–021302-5 (2010).
3. W. Song et al., "Reflection-mode in vivo photoacoustic microscopy with subwavelength lateral resolution," Biomed. Opt. Express 5(12), 4235–4241 (2014).
4. F. S. Foster, C. J. Pavlin, K. A. Harasiwicz et al., "Advances in ultrasound biomicroscopy," Ultrasound Med. Biol. 26(1), 1–27 (2000).
5. P. J. Westervelt, "Parametric acoustic array," J. Acoust. Soc. Am. 35(4), 535–537 (1963).
6. J. James and J. O. Norris, HSS White paper, American Technology Corporation, San Diego, California, USA, 2005.
7. P. Du, N. Jiang, and B. Song, “The directivity analysis of ultrasound-modulated audio directional transmission,” Audio Eng. 12, 40–45+52 (2015).
8. S. Bunch, S. S. Verbridge, J. S. Alden et al., “Impermeable atomic membranes from graphene sheets,” Nano Lett. 8(8), 2458–2462 (2008).
9. W. Li, Study on Acoustic Properties of Graphene Composites (Harbin Engineering University, 2019).
10. C. Ding, Y.-b. Dong, and X. Zhao, “Research progress on acoustic metamaterial and supersurfaces,” Acta Phys. Sin. 67(19), 194301-1–194301-14 (2018).
11. H. F. Zhang, K. Maslov, M. Sivaramakrishnan et al., "Imaging of hemoglobin oxygen saturation variations in single vessels in vivo using photoacoustic microscopy," Appl. Phys. Lett. 90, 053901 (2007).
J. Han and S. Tang, “Acoustic propagation characteristics of heteromorphic metamaterial,” AIP Adv. 8(10), 105305 (2018).

J. Han, S. Tang, R. Wang et al., “Acoustic wave transmission channel based on phononic crystal line defect state,” AIP Adv. 9(6), 065201 (2018).

J. Han, P. Yang, and S. Tang, “Local acoustic field enhancement of single cell photoacoustic signal detection based on metamaterial structure,” AIP Adv. 9(9), 095064 (2019).

S. Li, X. Li, F. Li et al., “Research progress on local resonance microstructure of acoustic metamaterial,” Inf. Commun. 11, 42–44 (2017).