High resolution photoacoustic system based on acoustic lens and photoacoustic sensors array

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Abstract

Photoacoustic tomography is a nondestructive bio-photonic imaging method based on the differences of optical absorption within biological organization. An approach using the lens with negative refractive index and photoacoustic sensors array to make the evanescent wave involved in the imaging process was presented in this paper. A set of comparative experiments was demonstrated on the imaging effect between the ordinary lens and the lens designed in this work. The experiment showed that the imaging effect of photoacoustic tomography by the designed lens had greatly outperformed the ordinary lens. In order to illustrate the good results, according to the characteristics of ultrasonic waves produced in photoacoustic effect, the propagation properties of the acoustic waves in lens with different refractive index was discussed. On the basis of analysing evanescent decay of ordinary acoustic lens which results in the loss of high-frequency information with image details in current photo-acoustic tomography system, the diffraction limit of was broken through and the image resolution was greatly improved by the lens with negative refractive index in theory.

Keywords: Photoacoustic Tomography, Acoustic Lens, Negative Refraction, Image Resolution

1 Introduction

With more and more technology development in computers, material, and industries, a considerable progress has been achieved on the photoacoustic tomography in medical ultrasound imaging. Recently, an earthshaking change has been made on new methods, techniques, and materials in the photoacoustic tomography, which also paves a way for the commercial applications of the photoacoustic tomography. The photoacoustic effect explains how electromagnetic energy can be absorbed and converted into acoustic waves. The photoacoustic tomography benefits from the advantages of pure optical or ultrasound imaging, without the major disadvantages of each technique. Especially its importance of studying and popularization is shown in the diagnosis on the early cancer conducted by Wang's group [1]. Since Veselago from the former Soviet Union proposed the concept of left-handed material [2] (negative refraction material) in 1968, the enthusiasm of scientists in the study of negative refraction materials has not been reduced. Especially in 2000, J.B. Pendry published an article named Negative Refraction Makes a Perfect Lens [3] on the Phys. Rev. Lett, which induced a series of discussions on the topic of negative refraction materials. Negative refraction acoustic lens are just the one kind of the lens compounded of different mediums. These mediums are compounded according to a certain rule, which share the characteristics of the negative refraction [4]. Moreover, this kind of lens has some merits, e.g., focusing, band gap, direction propagation, and etc. In addition, the characteristics of this kind of lens, e.g., focusing, filtering and directional control on acoustic wave, are very suitable for the improvement of the inherent disadvantages of the photoacoustic tomography.

Moreover, there are some typical experimental applications using photoacoustic tomography technology. For example, Ronald E. Kumon et al from the Department of Biomedical Engineering, University of Michigan @ Ann Arbor Campus, used the photoacoustic tomography technology to make a frequency-domain analysis on the prostate cancer tumor in the body of white rat, and achieved some good findings [5]. Xueding Wang et al from the Department of Radiological Sciences, University of Michigan @ Ann Arbor Campus, used the commercial imaging equipment combining with the detector developed by themselves to make images on a double of human hair and the treelike vascular of rabbit's ear, and acquired some quite clear images [6]. Hui Wang et al, who worked in the Key Laboratory of Laser Life Science, Ministry of Education, South China Normal University, used Fresnel zone plate ultrasonic detector to make images, and realized photoacoustic tomography [7]. Beside the examples above, some correlative studies on the technology of photoacoustic tomography were conducted in other research institutions as well. Overall, they mainly conducted their researches in two aspects:

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one is to use new materials, or to make the sensors array to ameliorate the receiving sensor, and the other is to use the new filtering and rebuilding algorithm of image to make a post-processing on the images. However, all of the studies did not solve the problems caused by the technology of photoacoustic tomography described above. Specifically, the spatial resolution of imaging is not high, and some tiny organizations still cannot be distinguished. In addition, when the imaging experiment is conducted on the living body, the quality of imaging is greatly affected by the complicated noise. Up to now, many researchers use acoustic lens to realize photoacoustic tomography [8-10], but few of them conduct on the application of negative refraction acoustic lens in photoacoustic tomography system.

In this work, with an analysis on the decay of the evanescent wave in the ordinary acoustic lens in current photoacoustic tomography system, an approach by using the lens with negative refractive index and photoacoustic sensors array to make the evanescent wave participate in the imaging process was proposed. In order to improve the resolution of images greatly, our research attempts to break through the diffraction limit of the ordinary acoustic lens. At the same time, the corresponding theory of acoustic information system was also investigated for better understanding of the performance.

2 The experimental Method

The acoustic lens photo-acoustic experiment system was built as shown in Figure 1. In order to distinguish different experiment effects of the lens, two kinds of refraction index lens to implement the experiment were chose. Four lasers YAG produced by the American company (Quanta-Ray PIV, Spectrum Physics) were used. The pulse repetition frequency is 25 KHz, pulse width is 10 ns, the wavelength is 1064 nm, and the incident light spot diameter is 1 mm. The sample used in the experiment was an artificial production with test panel of calibration. Panel was placed on the horsehair to show the different distances to display the maximum resolution of imaging system, which could be distinguished. The matrix surrounding sample box was liquid oil.

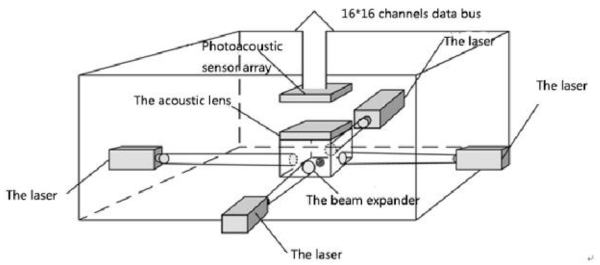


FIGURE 1 Experimental system of acoustic lens photoacoustic tomography

The acoustic lens was put on the sample box, and the acoustic sensor array was placed on the focus plane of the lens. To distinguish the contrast effects, two acoustic lens that one was the ordinary acoustic lens made of resin materials, and the other was negative refraction acoustic lens made of coat rubber layer embedded in epoxy resin were used [11-12]. Receiving array was the 16 × 16 micro-nano ultrasonic sensor, then connected to the data acquisition circuit after 16 × 16 channels data bus was connected.

Experimentation:

(1) Put the sample in the test platform of frosted glass vessels.

(2) Turn on the laser, through the beam expander and frosted glass beam expander, make the laser on the samples uniformly.

(3) The samples facing by laser irradiation will be heated up and expanded, then it will irradiate the acoustic wave. The acoustic wave through the acoustic lens (general lens and negative refraction lens) will focus on focal plane of photo-acoustic sensor array composed of 256 elements of 16×16.

(4) Photo-acoustic sensors make the acoustic signals of sample change into electrical signals. They get the analog signal through the filter amplifier signal conditioning, then the analog signals are converted to the digital signals. According to the principle of the lens, the two-dimensional image model of the hair.

(5) Transmit the characteristics of ultrasonic signal in the time and amplitude domain of each photo-acoustic sensor receiving into RAM, and combine with spatial information of acoustic lens imaging model, the final result of photo-acoustic tomography data can be got.

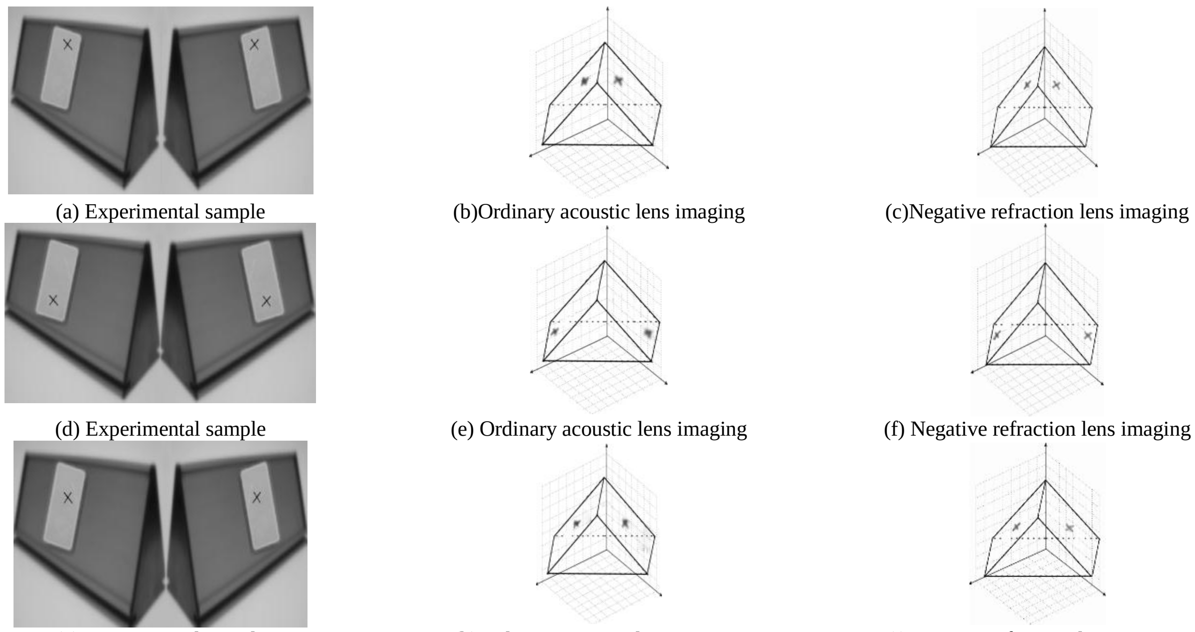
(6) After image post-processing, the final photo-acoustic tomography results can be obtained.

3 The experimental result and analysis

To examine the image resolution, a phantom sample with a cross of two-horse hair (65 μm diameter) in a block of transparent gelatine was made. This block of transparent gelatine is a rectangular thin plate with size of 4 mm × 1 mm. The block of transparent gelatine is placed on the tripod. Acoustic signals of the cross of two horse hair are generated by the laser irradiation, and the hair can be shown in the image after reconstruction. To understand the nature of the resolution improvement, photoacoustic imaging by the hair using different acoustic lens (ordinary lens and negative refractive index lens) was performed.

The experimental sample in Figure 2(a) shows that cross-shaped hair is on the top. The hair is irradiated by laser, and its imaging effect through ordinary lens is shown in Figure 2(b). The image is ambiguous, and the cross-shaped of the hair even cannot be identified. In order to distinguish imaging effect, negative refraction lens was used. If the hair is through laser's irradiating ultrasonic, its imaging effect through negative refraction lens is shown in Figure 2(c). The image is very clear and the cross-shaped of the hair is clearly visible. The experimental sample in Figure 2(d) shows that the cross-shaped hair is at the bottom. In Figure 2(e), the image through ordinary lens is fuzzy. From Figure 2(f), the image through negative refraction lens is very clear. In order to analyse the image resolution, we defined the resolution of an image as the width of the main lobe-crossing zero minus the width of the imaged hair. Here, we checked the image on the cross section of the hair. The photoacoustic images of the horsehair illuminated with the ordinary lens are shown in Figure 2(b) and 2(e). Here, the measured photoacoustic FWHM of the hair is found to be 235 μm on average.

Photoacoustic imaging with the negative refractive index lens provides both the highest SNR and the best resolution as shown in Figure 2(c) and 2(f). The measured FWHM of the horsehair decreases to 76 μm. In order to further verify the experimental results, we repeated the experiment in different positions. The experimental sample in Figure 2(g) shows that cross-shaped hair is in the centre position. Figure 2(h) and 2(i) show similar experimental results.



(a) Experimental sample (b)Ordinary acoustic lens imaging (c)Negative refraction lens imaging

(d) Experimental sample (e) Ordinary acoustic lens imaging (f) Negative refraction lens imaging

(g) Experimental sample (h)Ordinary acoustic lens imaging (i)Negative refraction lens imaging

FIGURE 2 Imaging results of Photoacoustic imaging system with different refractive index lens

According to the above experimental data, the measured photoacoustic FWHM of the hair the data was analysed in Table1. The resolution increases by three times compared to the acoustic resolution of the ordinary lens. Therefore, the photoacoustic tomography system with negative refractive index lens generally provides better spatial resolution, which is consistent with the theoretical analysis of the frequency dependence of spatial resolution.

TABLE 1 The measured photoacoustic FWHM of the hair

Different locations	**Ordinary acoustic lens (μm)**		**Negative refraction lens (μm)**	
	Left side	Right side	Left side	Right side
The hair on the top	234.81	234.61	76.14	76.18
The hair in the centre position	235.41	234.71	76.41	76.36
The hair at the bottom	234.95	234.82	76.48	76.42

Summarizing the above experiment images and combining with lens imaging knowledge, the limitation of the ordinary lens imaging system resolution leads to a virtual image of centring on the absorber and spreading outward. It makes the ambiguous intersection obviously. However, the image around the concentrated absorber (hair intersection) in negative refraction lens is very clear, it is easy to be identified and the image is consistent with the original sample. The result demonstrates perfectly that negative refraction lens is superior to the ordinary lens in terms of imaging resolution.

4 Discussion

4.1 ESTABLISHMENT OF THE DIFFERENT REFRACTIVE INDEX ACOUSTIC LENS MODEL

In order to describe the imaging resolution of different lens, the propagation of acoustic waves in different lens was analysed using COMSOL Multiphysics software. As shown in Figure 3, the nanosecond pulse laser irradiation is generally applied into the current photoacoustic tomography system to make an exposure on the detection area. When the detection is started, the detection area is expanded because of the heat of the laser. The coefficients of photoacoustic transition of the diseased and normal organization are different, which directly result in the difference between the thermal expansions of the media. Thus, different acoustic signals are generated in the two organizations. In addition, the signals can be received in the form of ultrasonic waves, and the distribution of the target can be shown in the image after reconstruction. Therefore, it can be concluded that the key to photoacoustic tomography is how to detect the ultrasonic signals. For the convenience, herein, the point radiating acoustic wave under the exposure of laser is assumed as point source reasonably in acoustic research, and the core of the study is how to detect the imaging information of the point source with high quality. Currently, some researchers have initiated the study on ordinary acoustic lens. To be more specific, as shown in Figure 4, the point source on the left side of the lens radiates waves under the exposure of laser, and the waves are gathered at the focal point on the right side of the lens using COMSOL Multiphysics software. In this work, the application of the negative refraction lens into the photoacoustic tomography system is put forward. The point source on the left side of the lens radiates waves under the exposure of laser, and the waves are gathered on the right side of the lens using COMSOL Multiphysics software, as shown in Figure 5.

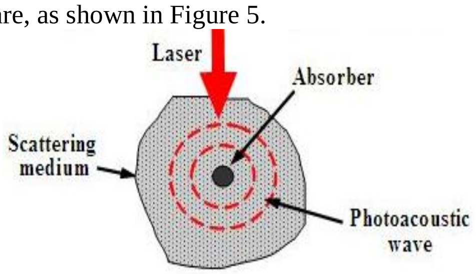


FIGURE 3 Thermal expansion of biological organization

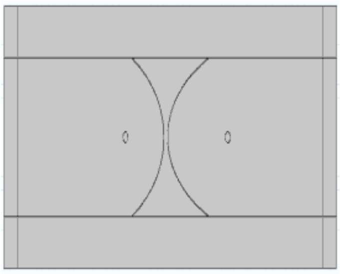


FIGURE 4 Diagrammatic sketch for the imaging of ordinary lens

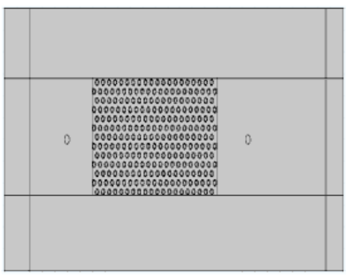


FIGURE 5 Diagrammatic sketch for the imaging of negative refraction lens

4.2 THEORETICAL SIMULATION ANALYSIS AND DISCUSSION

As a kind of ultrasonic waves excited by light, photoacoustic signal has all the characteristics of the waves substantially. Therefore, provided that, (1) a pulsed laser with uniform distribution (pulse width for the magnitude) is used to make exposure on the biological organization, and the dimension of photoacoustic signal generated by each point in the biological organization is proportional to the light absorption coefficient of the point in biological organization, and (2) each photoacoustic signal generated by the points in the biological organization is a point source with amplitude decayed by 1/r, and the function of the wave generated by the point source is $\varphi = Ue^{j\omega t}$, furthermore, in this function, U represents the complex amplitude of sound field [13-15]. When the acoustic wave is emitted onto the plane (x, y), there is a component for the wave propagated along the direction Z. According to the scalar wave equation of Helmholtz $\nabla^2 U + k^2 U = 0$, when the distance of propagation along the direction z of the wave is short enough, the solution to the wave equation can be expressed in the form of:

$$A(k_x, k_y, z_0) = A(k_x, k_y, z_0)e^{jk_z z_0}, \quad (1)$$

where $A(k_x, k_y, z_0)$ is the spatial spectrum distribution of the plane. Considering the sound velocity field v in front of the acoustic lens, the components of the field will be given by some 2D Fourier expansion

$$v(r,t) = \sum v(k_x, k_y)\exp(ik_x x + ik_y y + ik_z z - i\omega t). \quad (2)$$

Considering that the wave is propagated in the three-dimensional space, according to the relationship among k_x, k_y, and k_z the expressions k_x, k_y, k_z can be used to express the wave vector of free space. Therefore, the equation $k = \pm\sqrt{k_0^2 - (k_x^2 + k_y^2)}$ can be obtained, where $k_0 = 2\pi / \lambda$.

In the same time, considering that the index of refraction of the lens is either positive or negative, the equation

$$k_z = \pm\sqrt{k_0{}^2 - (k_x{}^2 + k_y{}^2)} = \sqrt{n^2\omega^2 / c^2 - (k_x{}^2 + k_y{}^2)}$$

can be deduced, where is positive in the positive refraction lens and negative in the negative refraction lens.

When $k_x{}^2 + k_y{}^2 > k_0{}^2$, so $k_z = j\sqrt{(k_x{}^2 + k_y{}^2) - k_0{}^2} = j\zeta$ (pure imaginary number). At present, the is a pure imaginary number, so

$A(k_x,k_y,z_0)=A(k_x,k_y,0)e^{-\zeta z_0}$, it leads to the resolution's limit of the lens $\Delta=2\pi/k_{\max}=2\pi c/\omega=\lambda$.

Obviously, when an acoustic wave propagates in the positive index lenses, wave vector k_z is changed into an imaginary number. The resolution limit is a wavelength. Although the radiation wave field phase of body surface carrying more fine structure information remains unchanged in the direction of propagation, the amplitude will have an exponential attenuation. This part carries high surface fine structure information of evanescent attenuation called evanescent wave. In Figure 6, it can be observed that the attenuation wave in positive refractive index lens. Therefore, the information carried fine structure cannot be propagated to the far field, and they are limited in the near-field area closed to the lens. It leads to the low resolution of ordinary lens, and it cannot meet the needs of photo-acoustic tomography. The decay of the evanescent wave in the ordinary acoustic lens results in the loss of the high-frequency information containing image details, so the effect of the imaging is not ideal, as shown in Figure 7.

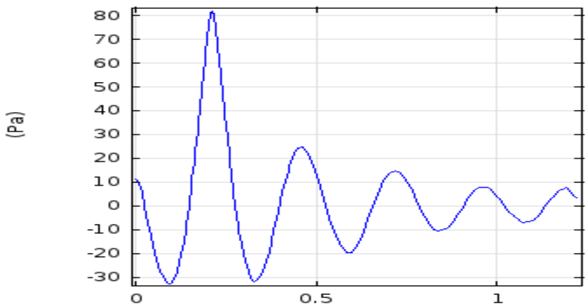


FIGURE 6 The evanescent wave of ordinary lens

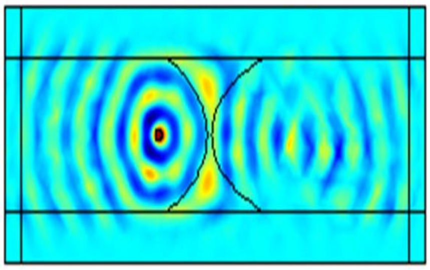


FIGURE 7 Diagrammatic Sketch for the Imaging of Ordinary Lens

If the transmission medium in the opposite direction was considered, when n<0, then $k_x^{\,2}+k_y^{\,2}>k_0^{\,2}$, so $k_z=-j\sqrt{(k_x^{\,2}+k_y^{\,2})-k_0^{\,2}}=-j\zeta$ (pure imaginary number), the Formula (1) can be expressed as:

$$A(k_x,k_y,z_0)=A(k_x,k_y,0)e^{-j^*j\xi_0}=A(k_x,k_y,0)e^{\xi_0}. \quad (3)$$

Although the propagation constants are changed into the imaginary, but the amplitude will be changed e^{ξ_0} as exponential form, acoustic amplitude along the Z direction is not decayed as exponential form. Calculations confirm that all of the energy is perfectly transmitted into the medium but in a strange manner. Overall, the transmission coefficient of the medium is

$$T=tt'=\exp\left(ik_z^i d\right)=\exp\left(-i\sqrt{\omega^2c^{-2}-k_x^2-k_y^2 d}\right), \quad (4)$$

where *d* is the slab thickness. It is this phase reversal that enables the medium to refocus sound by cancelling the phase acquired by the sound wave as it moves away from its source. To calculate the transmission through both surfaces of the slab, the multiple scattering events must be summed,

$$T=tt'\exp(ik_z'd)+tt'r'^2\exp(3ik_z'd)+tt'r'^4\exp(5ik_z'd)+...=\frac{tt'\exp(ik_z'd)}{1-r'^2\exp(2ik_z'd)}, \quad (5)$$

$$R=r+tt'r'e^{jk_z'd}+tt'r'^3e^{j3k_z'd}+\cdots=r+\frac{tt'r'e^{j2k_z'd}}{1-r'^2e^{j2k_z'd}}, \quad (6)$$

where *t* and *r* are the transmission coefficient and reflection coefficient at the interface within the medium respectively, *t'* and *r'* are the transmission coefficient and reflection coefficient at the interface between the medium and the vacuum, respectively. When the refractive index of the lens is close to -1, we can get the formula

$$\lim_{n\to-1}T=\lim_{n\to-1}\frac{tt'\exp(ik_z'd)}{1-r'^2\exp(2ik_z'd)}=\exp(ik_zd), \quad (7)$$

$$\lim_{n\to-1}R=\lim_{n\to-1}r+\frac{tt'r'e^{j2k_z'd}}{1-r'^2e^{j2k_z'd}}=0 \quad (8)$$

Therefore, the evanescent wave carrying surface fine structure information can retain well, it cannot be decayed just like the positive refractive index medium. We can use that transmission medium to break the diffraction limit when the refractive index is negative, so we can consider it to make the evanescent wave involve in the imaging. Then, the imaging is conducted by using the advantages of negative refraction lens, such as, focusing, filtering and directional control on acoustic wave.

Figure 8 shows that the evanescent wave in the flat lens is amplified exponentially, more and more high frequency component is able to transport, which can effectively compensate the exponential decay of evanescent wave in the water. So that it can be successfully transferred to the image plane and involved in the imaging, and the negative refraction lens in the photo-acoustic tomography was used. Figure 9 is a simplified model for the photo-acoustic tomography, and it is consistent with that in Figure 7, which shows that the model is reasonable.

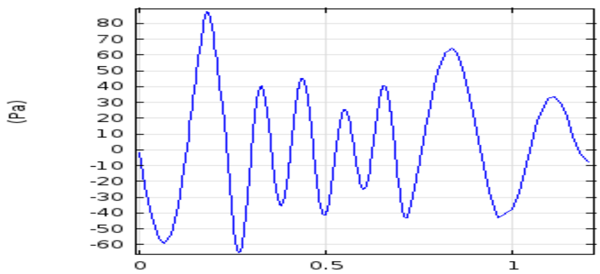


FIGURE 8 The enhanced evanescent wave of negative refraction lens

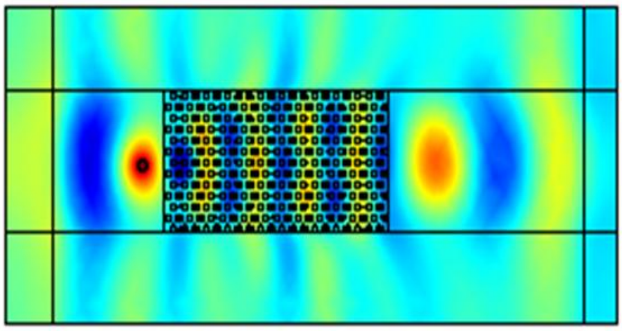


FIGURE 9 Amplified analog effect for the negative refractive imaging

In Figure 10 (a) and 10(b), according to the experimental device in this paper, the simulation environment was adjusted. The equivalent of experimental equipment illustrated the negative refractive index lens imaging effect. From the result of simulation, after the original point source through negative refraction lens, it converges into a clear image point on the right side of the lens. From the point in the waveform as shown in Figure 10(c), the resolution of the lens reaches 0.3 wavelength. So the scheme of the lens is a better design for the high resolution photo-acoustic tomography both theoretically and practically.

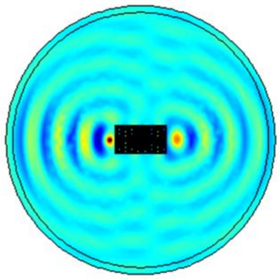


FIGURE 10 (a) Simulation effect of the negative refractive imaging

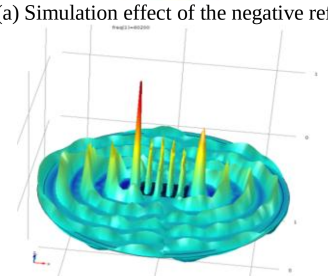


FIGURE 10 (b)3D simulation effect of the negative refractive imaging

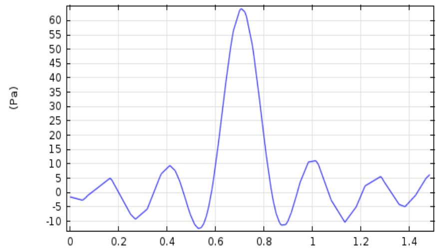


FIGURE 10 (c) Sound pressure distribution of the focus image point

5 Conclusions

In this paper, through lens imaging model, the imaging effects of the cross-shaped hair was analysed, and the best imaging effect through comparisons of many experiment samples was obtained. It proved that the imaging effect of negative refraction lens is better than that of normal acoustic lens. Then the phenomenon that the photo-acoustic tomography of negative refraction index lens can enhance the evanescent wave and the evanescent decay of ordinary acoustic lens with image details makes the resolution sharply were discussed . The enhanced evanescent wave makes the evanescent wave take part in the imaging, which greatly increases the resolution ratio of lens imaging. It also plays an important role in enhancing photo-acoustic tomography in the field of medical research and clinical examination. As for the weaknesses of our approach, the unit of sensor array was small, which limited the power of higher resolution ratio. In addition, normal image processing in image post-processing was used. If more advanced image processing techniques can be employed, better image resolution even can be achieved.

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