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# Wavelength-scale gas-filled cuboid acoustic lens with diffraction limited focusing

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ABSTRACT

Per the laws of geometrical optics, a plane-parallel medium does not possess focusing properties. However, in this paper, we demonstrate for the first time that an acoustic cuboid particle filled with $CO_2$ is able to focus sound despite its flat surface. It is worth noting that traditional lenses focus sound through their curved surfaces. We report both numerically and experimentally the acoustic focusing of a cuboid of 2λ side, where λ is the wavelength in air. From these results, it can be derived that its focusing capabilities are close to the diffraction limit: at frequency of 5000 Hz, acoustic beam waist is about 0.5 wavelength and the gain is 8.8 dB. The flat structure lens proposed open new possibilities to design and built new lightweight and low cost acoustic lenses for different applications.

## Introduction

Sound interferes with us in daily life in different areas in such a way that studies of different properties of the mechanisms of sound generation and focusing should be carried out to achieve the most efficient mechanisms for each application. Acoustic lenses can be applied in different areas of physics, engineering and even in medicine. However, it is still a challenge to carry out its implementation due to the compromise that must exist between there being a high contrast of speeds and a good coupling of impedances to achieve a good transmission.

Currently there are different types of acoustic lens designs based on different physical phenomena: lenses based on Fresnel diffraction [1], lenses based on 2D and 3D phonics crystals [2–5], lenses that use acoustic metamaterials based on acoustic gradient index (GRIN) [6,7] and hyperbolic GRIN [8,9], those that use metamaterials based on Helmholtz resonators or split ring type resonators [10], etc. Nevertheless, there are not many naturally occurring materials with the properties needed to build sound lenses. The other possibility to obtain acoustic lenses is through gas-filled spherical lenses. However, there are few references about their design characteristics and fabrication to obtain a convergent behaviour [11–14]. The possibilities of diffraction limited focusing were not investigated here. It could be mentioned that today, spherical acoustic gas filled lens is used, for example, for sound focus speaker [15].

Acoustic lenses focus sound in the same way as optical lenses focus light because the underlying theory is applicable to different kinds of waves. Thus, the acoustics lenses have the same constraints that electromagnetic ones have, that is: limited to a half-wavelength resolution due to diffraction theory. In this sense, in the linear mode, it would be expected that photonic jet (PNJ) phenomenon [16] that allows subwave focusing in optics, behave in the acoustic range in the same manner as in the optical range does.

This fact has led to propose the so called "acoustojets" phenomenon (AJ) in acoustics [17], which is based on the ideas of PNJ phenomenon. The existence of the acoustic similarity of PNJ, has been already theoretically predicted [17,18], which potentially open the doors to a subwavelength focalization size. That means a significant increase of acoustic pressure in the shadow zone of an arbitrary mesoscale particle.

A key problem of this possibility is acoustic impedance. If the impedance of a lens matches that of its background - for example, the air surrounding it - then the transmission ability of the lens is far higher. Theoretical investigations of natural material-based ball-lens (polyethylene, silver, lead, etc) with subwavelength focusing based on acoustojet phenomenon were presented in Ref. [18]. Solid spheres of different metals, such as stainless steel, brass, and tungsten carbide are able to produce subwavelength acoustojets [17,18]. However, their impedances do no match with that of the surrounding medium so that the intensity is relatively low. Recently, experiments with a Rexolite sphere, of a diameter of 8.231 wavelengths immersed in water, verified the AJ phenomenon at 1.01 MHz [19]. The transverse resolution was

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about 0.52 of wavelength in surrounding medium. Similar experimental results were obtained for a cylindrical particle-lens too [20].

It is necessary to emphasize that to study the propagation of the acoustic waves through the AJ the Navier-Stokes equations must be applied, since the effects of the AJ cannot be predicted from the geometric optics or from the scalar diffraction theory [21]. In the same way, it is worth noting that, in optics, the photonic jet is formed in the near field, a region in which scattering plays an important role [21]. This implies that the size of the element or particle is limited, that it ought to have a mesoscale dimension, that is, to be of a few wavelengths and even equal to the wavelength of the radiation [21]. Therefore, what is important is not the concrete value of the incident wavelength, but that its relation to the size of the particle or element fulfils the mesoscale condition [17,21]. For this reason, throughout the work, we will not use the absolute values of geometric parameters but the values relative to the length of the incident wave in the air. Therefore, below we do not use absolute values of geometric parameters, but relative ones in the unities of the incident wavelength in air.

However, as solids, from which lenses could be easily manufactured, have acoustic impedance much higher than air, refracting lenses or particle-lenses are difficult to implement in air. Taking into account that acoustic impedance is the product of compressional wave speed and density, its high contrast between the solid and air means that the incident wave on the solid virtually would be reflected rather than refracted at the edges of the lens [22]. It is well known that spherical gas-filled lenses allow sound to be focused, but extrapolation to flat wavelength-scaled cubic particle gas filled lens is not self-evident because its shape is similar to flat-parallel plates and according to the laws of geometric optics, such a lens will not focus the sound wave incident on it. So, the main aim of the paper is to show the acoustic focusing capabilities of a $CO_2$ filled cubic lens. We verify both simulations and experimental the airborne sound focusing through a lens with planar surfaces, breaking the geometric acoustic laws. The focusing capabilities of the lens are analysed with regards to the descriptive parameters of the focused beam, such as sound pressure (or pressure gain), focus position along the longitudinal axis and Full Width at Half Maximum (FWHM), which is the width of the beam intensity at $-3$ dB [19,20].

## Experimental set-up

In order to mathematically implement the characteristics of the system and to physically analyse the problem involved, a Finite Element Method (FEM) has been used by means the 3D Acoustic Model of COMSOL Multiphysics Modelling [23]. To avoid the high computational cost that 3D modelling requires, only half of the domain was simulated. This was possible because a symmetric boundary located at the centre of the model was defined to emulate a mirror-plane. Perfect Matched Layers were used to model free field conditions. A Free tetrahedral mesh was used, with a minimum element size of $\lambda/10$ and a maximum element size of $\lambda/8$. The values of sound speed (c) and density ($\rho$) used for $CO_2$ and air were $c_{CO2} = 260$ m/s, $\rho_{CO2} = 1.977$ kg/m$^3$, $c_{air} = 343$ m/s, $\rho_{air} = 1.21$ kg/m$^3$. The intensity gain in the focus was calculated by means the expression $10\cdot\log(I(x, y)/I_{incident}(x, y))$, where $I(x, y)$ is the intensity at focus and $I_{incident}(x, y)$ is the incident intensity.

To characterize the cube lens behaviour, a cubic structure with 160 mm side was built using a 3D printer. To leave a closed volume and keep the $CO_2$ gas inside, the entire cubic structure was covered with a thin plastic film and filled with $CO_2$ gas. Once the cuboid was filled and a $CO_2$ concentration of 90 ± 5% reached, the holes used to introduce $CO_2$ gas inside the volume were sealed. The experimental measurements were performed in an anechoic chamber of dimensions $8 \times 6 \times 3$ m$^3$, where the cube was hanged from a frame to avoid ground effect. A sound source (GENELEC 8040A) emitting white noise was place 2.4 m away from the cube to consider the wave impinging on

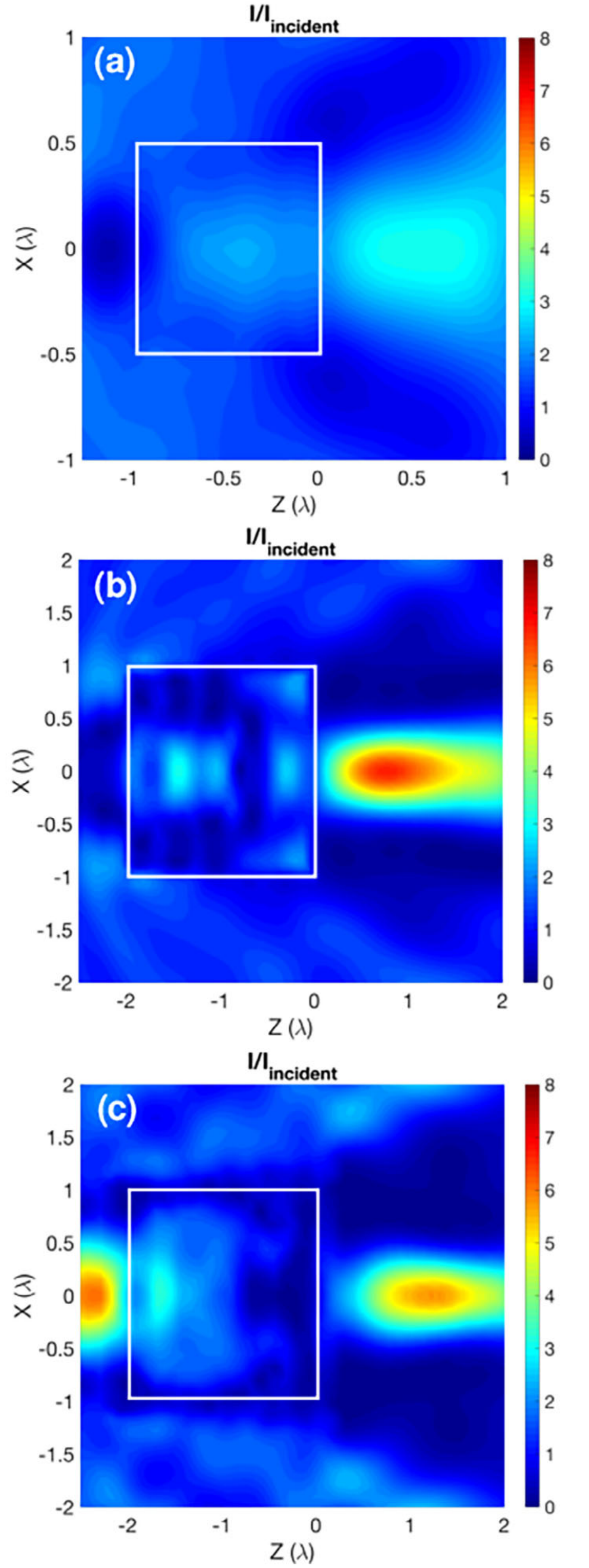


**Fig. 1.** Normalized sound intensity distributions for cubic gas-filled lenses at 2062 Hz (a), 4125 Hz (b) and 5000 Hz (c), respectively. Sound wave moved from left to right.

the cube could be considered as plane wave. A bi-dimensional robotized measurement system was used to position and a prepolarized free-field 1/2″ microphone (Type 4189B&K) in plane predefined trajectories.

## Results and discussion

To illustrate the focusing properties of extremely small size dimensions of a cubic lens equal to wavelength, the effects of sound wave focusing are shown in the Fig. 1(a–c). Sound wave traveling from air into a flat surface of a lens is affected by diffraction at the lens surface as its diameter approaches the wavelength of sound. The Normalized Sound Intensity wave is shown in the same scale for three frequencies of incident wave. In the units of wavelength, the frequencies of 2062 Hz, 4125 Hz and 5000 Hz correspond to the cube dimensions of λ, 2λ and 2.33λ, respectively. It is clearly seen that the region of pressure localization of the acoustic field begins to form at a cubic lens size equal to one wavelength (2062 Hz, Fig. 1a). However, intensity is low. With a cube side size of two wavelengths (4125 Hz, Fig. 1b), the focusing region near the shadow surface of the lens is clearly formed. With a further increase in the effective size of the cube (5000 Hz), the focusing region narrows, and a second region of localization of the sound field appears in the wave reflected from the illuminated surface of the cube. When lens diameter is reduced to nearly the wavelength of sound wave, diffraction of the input beam at the lens surface causes variations in phase and amplitude that affect focusing inside the lens.

The transverse dimensions of the region of the localization of the sound field (lenses resolution), depending on the frequency of the incident wave (the size of the cube) are characterized by the graphs shown in the Fig. 2 and summarized in the Table 1. From the presented data, it follows that the diffraction limited resolution of the flat gas-filled lens under consideration is achieved starting from the size of the side of the cube into two wavelengths.

The results of experimental measurement focusing characteristics of cubic gas-gilled lens are presented in the Fig. 3 and are as follows: at frequency of 4120 Hz, FWHM is 0.63λ and the intensity (Gain) at the focus is 9.1 dB. At frequency of 5000 Hz, FWHM is 0.54λ and the Gain at the focus is 8.8 dB.

From Fig. 3(a) it is clearly visible that the acoustic energy in the host medium is focused into a shape like sound bullet [24,25] a compact subwavelength region of high energy density. Also from the Fig. 3(b) it is followed that the resolution of gas-filled lens with small dimensions of 2λ × 2λ × 2λ is close to diffraction limit. The asymmetry of the acoustic transmitted beam near z = 1.2–1.4 on the Fig. 3 in our opinion, is believed to be due to a slight misalignment of the cuboid during the measurement process.

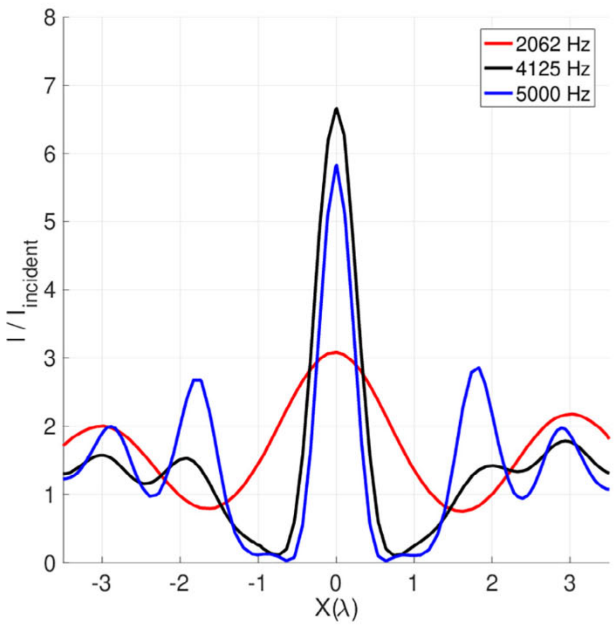


**Fig. 2.** Transverse relative sound intensity distributions ($I/I_{incident}$) in the focus of cubic particle-lens at three frequencies.

**Table 1**
Numerical focusing characteristics of the gas-filled cubic lens.

| Frequency (Hz) | FWHM (λ) | Intensity gain at the focus (dB) |
|---|---|---|
| 2062 | 1.48 | 4.9 |
| 4125 | 0.64 | 8.2 |
| 5000 | 0.5 | 7.6 |

Physically, the focusing capability of these flat-faced acoustic lenses, filled with $CO_2$, can be explained by the velocity profile inside the cuboid. When the incident plane wave impinges the cuboid and penetrates into this new medium, near the separation surface, the velocity of the pressure wave is greater at the edges than at its centre. These velocity differences give rise to a deformation of the wave front, going from convex to concave on the opposite side to the incidence one. In our case, the acoustic impedance contrast is more than 1.15, the contrast of the sound velocity more than 0.88, and the size of the cuboid or acoustic particle greater than the wavelength. These characteristics favour that the wave front acquires a positive curvature, which favours the condition of sound focusing. Therefore, it is not the shape of the lens or particle that favours focusing as it does in the case of the sphere filled with gas. In this case, the phenomenon responsible for focusing is refraction while in the case of the cuboid it is the diffraction of the incident wave, which plays the main role in focusing through these flat-faced acoustic lenses.

To illustrate the mechanism of focusing, in Fig. 4, the Root Mean Square (RMS) sound speed map is shown and the formation of positive curvature of speed near the shadow surface of cube is clear visible. This phenomenon corresponds to the focusing conditions [26]. The mechanism of convergence of such a wave front in the focusing region has been well studied, and in our case, it does not differ from the known mechanism [26].

## Conclusions

In conclusion, a new flat-faced acoustic lens was designed and built. This new type of acoustic element will enable new types of sound focusing devices, although it is known from the laws of geometric optics that a plane-parallel medium does not possess focusing properties. The numerical simulations and experiment demonstrate the focusing effect of $CO_2$-filled cubic lens at audible sound frequencies. The FEM numerical prediction and the experimental results are in good agreement showing enhanced diffraction limited focusing properties never observed before in this kind of flat gas filled lenses with wavelength scaled dimensions.

The acoustics energy is focused in a subwavelength region size, known as sound bullet, where an increase of energy density takes place. The characteristics of this region such as, amplitude, size, and location can be controlled by varying the gas concentration in the cube. This simple mesoscale (1–2 of wavelength dimensions) gas-filled lens, due to the simplicity of this flat-face design, our findings open new possibilities in lensing applications in different branches of science and technology and may have a great impact on the physics of sound, from aeroacoustics to ultrasound therapy (with corresponding selection of acoustic impedance and speed of sound contrast of medium in a lens). It seems the smallest dimensions of a lens comparable to the wavelength ever recorded for any acoustical lenses. Given the simplicity of the flat design, our findings open new possibilities in lensing applications in different branches of science and technology and may have a great impact on the physics of sound. The flat superlenses can be readily

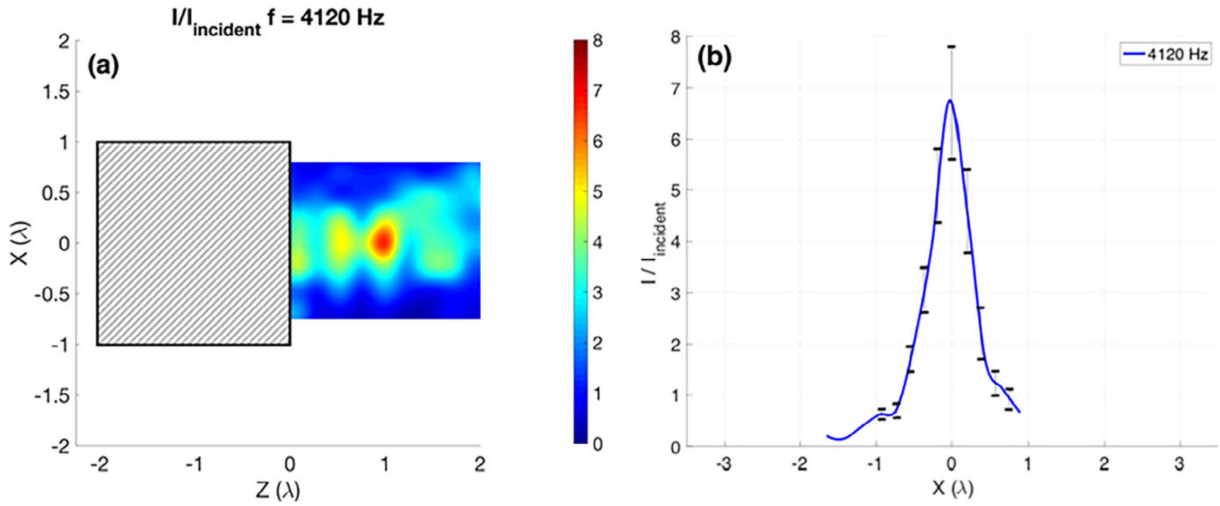


**Fig. 3.** Experimental relatively sound intensity map (a) and transverse resolution (b) of cuboid lens.

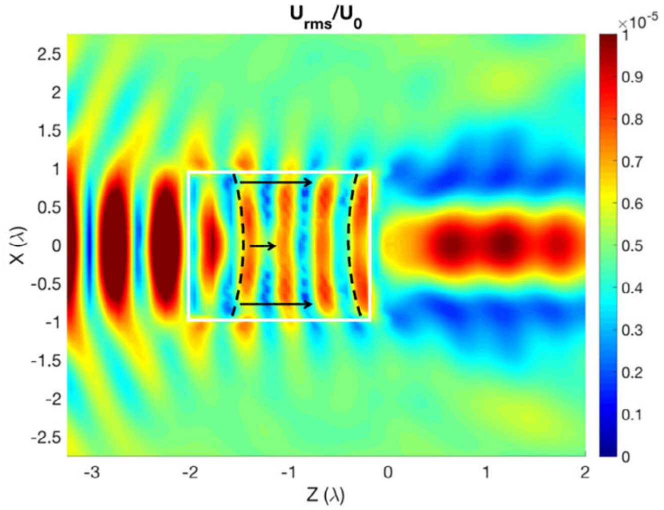


**Fig. 4.** The RMS sound speed map at 4125 Hz. The dotted line shows the changes of the wave front curvature.

adapted to sound imaging systems as well as acoustic microscopy technology.

The results of this work may reasonably assume that such acoustic gas-filled lenses can be of quite arbitrary shape (if the mesoscale dimension criterion is observed), as was shown in optics and electromagnetics [21,27].

Additionally, the high-energy gradients found in subwavelength focusing area may prompt this lens be used in sound tweezers for contact-less particle manipulation.

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## References


[1] Hadimioglu B, Rawson EG, Lujan R, Lim M, Zesch JC, Khuri-Yakub T et al. High-efficiency Fresnel acoustic lens. IEEE IUS 1. 1993. 579.

[2] Miyashita T, Taniguchi R, Sakamoto H. Experimental full band-gap of a sonic-crystal slab structure of a 2D lattice of aluminium rods in air. In: Proceedings of the 5th World Congress on Ultrasonics. Paper No. TO-PM04.02. 2003.

[3] Kaya OA, Cicek A, Ulug B. Focusing with two-dimensional angular-symmetric circular acoustic lenses. Acoust Phys 2011;57:292.

[4] Cervera F, Sanchez-Perez JV, Martinez-Sala R, Rubio C, Meseguer F, Lopez C, et al. Refractive acoustic device for airborne sound. Phys Rev Lett 2001;88:023902.

[5] Sukhovich A, Merheb B, Muralidharan K, Vasseur JO, Pennec Y, Deymier PA, et al. Experimental and theoretical evidence for subwavelength imaging in phononic crystals. Phys Rev Lett 2009;102:154301.

[6] Romero-Garcıa V, Cebrecos A, Pico R, Sanchez-Morcillo VJ, Garcıa-Raffi LM, Sanchez-Perez JV. Wave focusing using symmetry matching in axisymmetric acoustic gradient index lenses. Appl Phys Lett 2013;103:264106.

[7] Li Y, Yu G, Liang B, Zou X, Li G, Cheng S, et al. Three-dimensional ultrathin planar lens by acoustic metamaterials. Sci Rep 2014;4:6830.

[8] Wang W, Xie Y, Konneker A, Popa B, Cummer SA. Design and demonstration of broadband thin planar diffractive acoustic lenses. Appl Phys Lett 2014;105:101904.

[9] Moleron M, Serra-Garcia M, Daraio C. Acoustic fresnel lenses with extraordinary transmission. Appl Phys Lett 2014;105:114109.

[10] Yang X, Yin J, Yu G, Peng L, Wang N. Acoustic superlens using Helmholtz-resonator-based metamaterials. Appl Phys Lett 2015;107:193505.

[11] Atkinson E. Elementary treatise on physics, experimental and applied, New York, eleventh ed. 1882. p. 237.

[12] Kruglak H, Kruse CC. A visual method for demonstrating refraction of sound. Am J Phys 1940;8:260.

[13] Kendall JM. Acoustic Lens is Gas-Filled NASA Tech Briefs, 5, (1980), 345.

[14] Thomas DC, Gee KL, Turley RS. A balloon lens: acoustic scattering from a penetrable sphere. Am J Phys 2009;77:197.

[15] Lee, JM. Sound focus speaker of gas-filled sound lens attachment. US Patent 7,204, 342 B2. 2007.

[16] Lukiyanchuk BS, Paniagua-Domnguez R, Minin IV, Minin OV, Zengbo W. Refractive index less than two: photonic nanojets yesterday, today and tomorrow Opt. Mater Express 2017;7:1820.

[17] Minin IV, Minin OV, Acoustojet: acoustic analogue of photonic jet phenomenon. arXiv:1604.08146. 2016.

[18] Minin OV, Minin IV. Acoustic analogue of photonic jet phenomenon based on penetrable 3D particle Opt. Quant Electron 2017;49:54.

[19] Lopes JH, Andrade MAB, Leao-Neto JP, Adamowski JC, Minin IV, Silva GT. Focusing acoustic beams with a ball-shaped lens beyond the diffraction limit. Phys Rev Appl 2017;8:024013.

[20] Minin V, Minin OV. Mesoscale acoustical cylindrical superlenses MATEC 155. 2018. 01029.

[21] Minin Igor V, Minin Oleg V, Geints Yuri E. Localized EM and photonic jets from non-spherical and non-symmetrical dielectric mesoscale objects: brief review. Ann Phys (Berlin) 2015;527:491.

[22] Martin JS, Fenneman DJ, Codron F, Rogers PH, Scott WR, Jr., Larson GD, et al. Ultrasonic Displacement Sensor for the Seismic Detection of Buried Land Mines AEROSENSE 4742. 606. 2002.

[23] COMSOL Multiphysics. Comsol multiphysics user guide (version 4.3a). COMSOL, AB, 2012. p. 3940.

[24] Spadoni A, Daraio C. Generation and control of sound bullets with a nonlinear acoustic lens. Proc Natl Acad Sci 2010;107:7230.

[25] Donahue CM, Anzel PW, Bonanomi L, Keller TA, Daraio C. Experimental realization of a nonlinear acoustic lens with a tunable focus. Appl Phys Lett 2014;104:014103.

[26] Lucas BG, Muir TG. The field of a focusing source. J Acoust Soc Am 1982;72:1289.

[27] Minin IV, Minin OV. Diffractive optics and nanophotonics: resolution below the diffraction limit. New York: Springer; 2016.