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Sound focusing of wavelength scale gas-filled flat lens

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Abstract – The capability of focusing of a novel acoustic lens based on mesoscale acoustic cuboid particle filled with CO_2 gas is analysed. This flat lens is able to focus sound in the same way that conventional curved acoustic lenses do. It is shown that the sound speed inside the cuboid is the responsible for this effect. By changing the percentage of CO_2, the sound speed inside the cube changes and therefore the focusing properties. The focusing effect is numerically investigated and experimentally validated. The results obtained allow the design of new flat low cost acoustic lenses with wavelength-scale dimensions for different applications.

Introduction. – Acoustic lenses have always attracted scientific interest because they can be widely applied in many areas. Based on the different mechanisms that can produce the focusing of sound, different types of acoustic lenses have been proposed over the years, such us Fresnel lens [1] slabs composed 2D and 3D phononic crystals [2, 3, 4], acoustic gradient index lenses [5, 6], lens based on split-ring type resonators [7], space-coiling lenses [8,9], axisymmetric grating lens [10], etc.

The phenomenon of the Photonic Jet (PJ), that is a highly localized intensive optical flux caused by dielectric objects, has received a growing interest in exploring their basic characteristics [11]. The photonic jets depends on the contrast of the refractive index, and the size and geometry of the particle. It was found that in addition to microspheres and cylinders, the dielectric cuboid particles can also generate photonic jets [12, 13].

Motivated by the wave nature of light and sound, the research in electromagnetic waves have been transferred to acoustic waves. The existence of an acoustic analogue to the photonic jet was demonstrated for the first time by Minin's [14, 15] and they called the phenomenon "acoustojets". Underwater ultrasound has been chosen to confirm experimentally a high acoustic field localization in shadow area of a spherical Rexolite particle-lens with a diameter of 8.25 λ, where λ is the wavelength of the incident wave [16].

In this letter, we show both numerically and experimentally, that a CO_2 gas-filled flat cuboid particle of dimensions equal to two times the incident wavelength can focus airborne sound in the same way that curved acoustic lenses do. It is shown that when a plane wave impinges on the gas-filled cuboid particle and penetrates into the CO_2 gas medium, the difference in sound velocities causes deformation of sound pressure wave front, which results in sound focusing. In this case, when dealing with flat surfaces, the main role is the wave diffraction, and not the refraction. As the phenomenon of focusing depends on sound velocities we show through simulations the influence of sound velocity of the gas inside of such gas-filled lens on sound focusing, which is not obvious for a cubic acoustic lens. In nature, there are only few gases, for which sound velocity and acoustic impedance are suitable for creating such lenses. The sound speed of CO_2 gas is lower than air, which is reason why when varying the percentage of CO_2 gas inside the cuboid, the sound velocity in the mixture will vary. This fact will cause variations in the deformation of the wave front produced by the focusing.

Numerical modelling. – The simulation results were obtained by using a 3D Acoustic Model of COMSOL Multiphysics Modeling©. In the simulations, a symmetric boundary located at the center of the model was defined to emulate a mirror-plane to avoid the high computational cost required by this model. The free field conditions for the outgoing waves were modelled using Perfect Matched Layers [17]. To avoid numerical dispersion, the maximum element

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size was λ/8 and a minimum element size was λ/10. In the simulations, the CO_2 was modeled with sound speed of c_{CO2}=260 m/s and density equal to ρ_{CO2}=1.977 kg/m^3, whereas the value used to model air were c_{air}=343 m/s and ρ_{air}=1.21 kg/m^3. Six different percentages of CO_2 were considered: 100%, 90%, 80%, 70%, 60% and 50%. Table I shows the gas mixture density, sound speed and acoustic impedance as a function of CO_2 gas percentage inside the cuboid.

Table 1: Gas mixture density, sound speed and acoustic impedance as a function of CO_2 gas percentage inside the cuboid.

%CO2	Gas mixture density (kg·m^3)	Gas mixture sound speed (m·s^{-1})	Gas mixture Acoustic Impedance (kg·m^{-2}·**s**$^{-1}$**)**
100	1,98	260,00	514,02
90	1,90	268,30	509,85
80	1,82	276,60	504,41
70	1,75	284,90	497,69
60	1,67	293,20	489,70
50	1,59	301,50	480,44

Experimental set-up. – To validate the numerical results obtained, a set of experiments have been performed. The basic structure considered is a cubic structure with 160 mm side that was built using a 3D printer. To keep the CO_2 gas inside the cuboid a thin plastic film was used to cover the all the structure, which left a closed volume. Two holes were made in the cuboid: a hole to introduce CO_2 and another to let in air and maintain atmospheric pressure (CO_2 is heavier than air, so it would displace the air). Once the final pressure was reached, the holes were sealed, the CO_2 concentration was measured with a gasometer and, finally, the areas where the holes were made were covered with septum and then sealed. A CO_2 concentration of 90 ± 5% was used throughout measurements. The frequency of work was 4125 Hz, so the cuboid dimensions correspond to two wavelength of the incident wave.

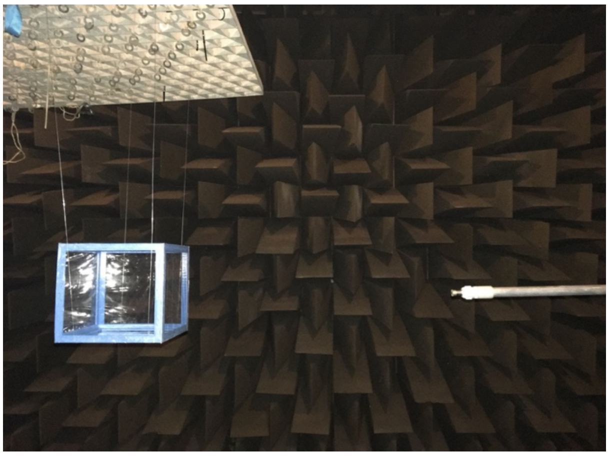

Fig. 1: (Colour on-line) Detail of the experimental set-up. Cuboid CO_2-filled lens in the anechoic chamber.

To simulate free field conditions in experimental measurements, the cube was hung from a frame in an anechoic chamber of dimensions 8x6x3 m^3. The cuboid was placed 2.4 m away from a sound source (GENELEC 8040A) that emitted white noise where the cube was hung from a frame to avoid ground effect (see Figure 1). The position of the prepolarized free-field 1/2" microphone (Type 4189 B&K) was controlled and varied by a bi-dimensional robotized measurement system. The source-receiver line was always perpendicular to the length of the sample. The signal adquired by the microphone was saved on the computer and by using the Fast Fourier Transform (FFT) the frequency response of the measured sample was obtained. An area of 240 x 480 mm^2 was mapped in steps of 15 mm or λ/4. The measurement average time per one point was about 15 sec.

Results. – Figures 2(a)-(f) show the normalized sound intensity distributions for CO_2 filled cuboid lens for the different CO_2 percentages considered. It is clearly observed that as the percentage of CO_2 inside the cuboid decreases, which would correspond to an increase in the sound speed of the mixture of gases inside the cube, approaching the sound speed of the air, the intensity of the focus decreases, while moving away from the cuboid. In this case, by focusing, we mean the localization of the pressure (with an intensity several times greater than in the incident wave) in the region of the shadow surface of the lens. It is also observed that a reduction of the percentage of CO_2 from 100% to 90% causes a significant decrease in the intensity at the focus, while in the following reductions in CO_2 percentage the reductions in intensity at the focus are gradual. This fact can be observed more clearly in Figure 3 where the transverse relative sound intensity distributions in the focus of cubic particle-lens are shown. From the Figure 3 it is also followed that the resolution of such flat lens changes from 1.01λ at 50% to 0.64λ at 100%. This phenomenon can be explained by the fact that when the plane wave incident on the cuboid lens penetrates in the interior. The acoustic disturbance near the edges of the cuboid propagates with greater phase velocity than in the center of the cuboid which causes that the wavefront inside cube to become concave at the shadow side of the lens due to an interference of the diffracted waves from the both edges of the cuboid and the wave coming through the cuboid, instead of being convex near the illuminated side of the lens. This one can be observed more clearly in Figure 2(a')-(f') where the relative sound speed distributions in the focus of cubic particle-lens as a function of CO_2 percentage are shown. As the concentration of CO_2 inside the cuboid is reduced, the sound speed increases so that the deformation of the wavefront is smaller due to the lower relative sound speed with respect to the air outside the cuboid.

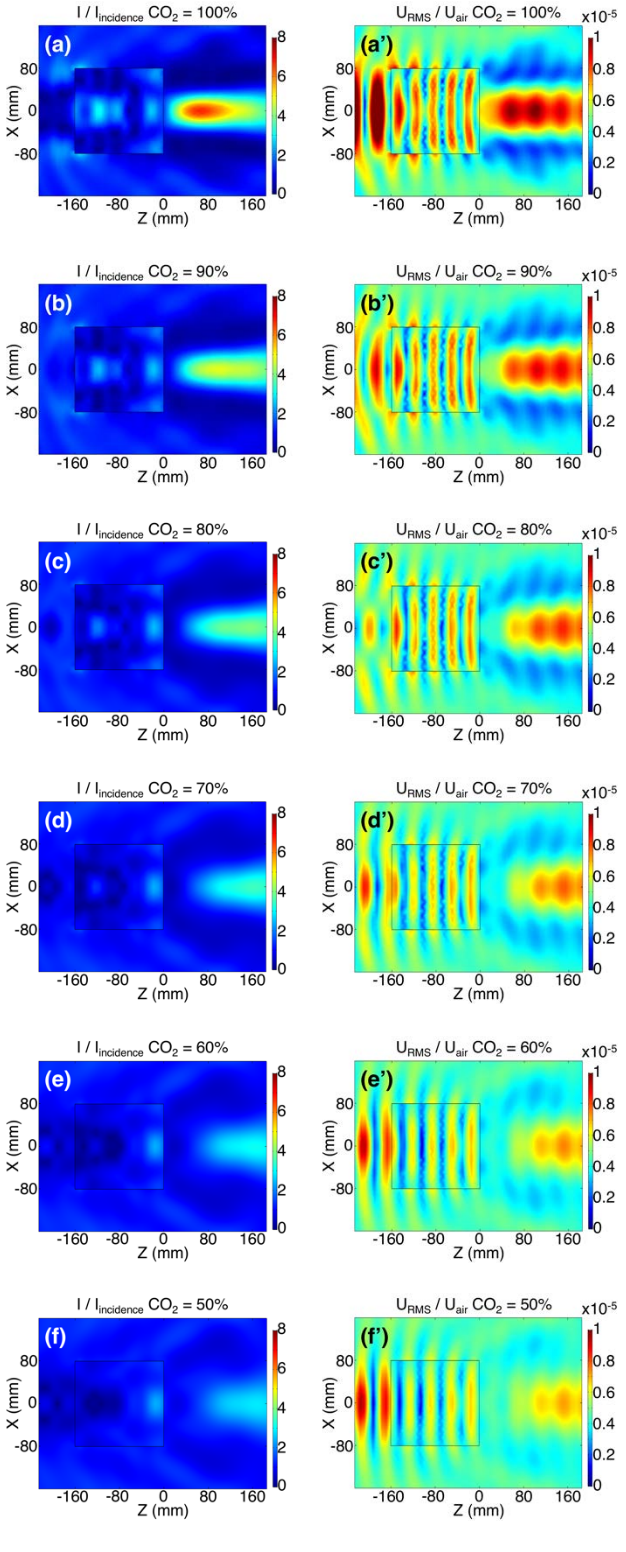

Fig. 2: (Colour on-line) Normalized sound intensity distributions for CO_2 filled cuboid lens for different CO_2 percentages: (a) 100%, (b) 90%, (c) 80%, (d) 70%, (e) 60% and (f) 50%, and normalized sound velocity maps for CO_2 filled cuboid lens for different CO_2 percentages: (a') 100%, (b') 90%, (c') 80%, (d') 70%, (e') 60% and (f') 50%.

Figure 4(a) shows longitudinal relative sound intensity distributions of cubic particle-lens and Figure 4(b) shows the variation of the focal length as a function of CO_2 percentage inside the cuboid lens. It can be observed that as the percentage of CO_2 inside the cuboid decreases, the focal length increases. It should be noted that reducing the percentage of CO_2 from 100% to 90% and from 90% to 80% causes a significant increase in the focal length. However, when the percentage of CO_2 inside the cuboid reaches 70%, the focal distance is maintained with very slight variations.

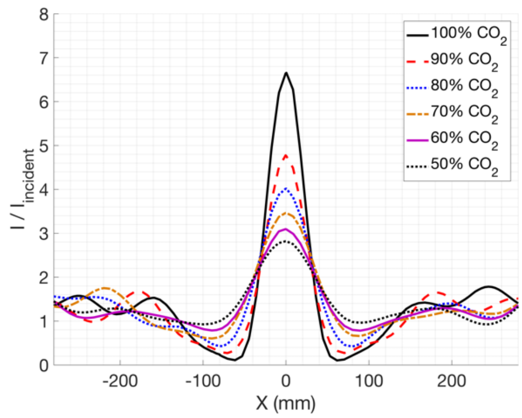

Fig. 3: (Colour on-line) Transverse relative sound intensity distributions in the focus of cuboid lens.

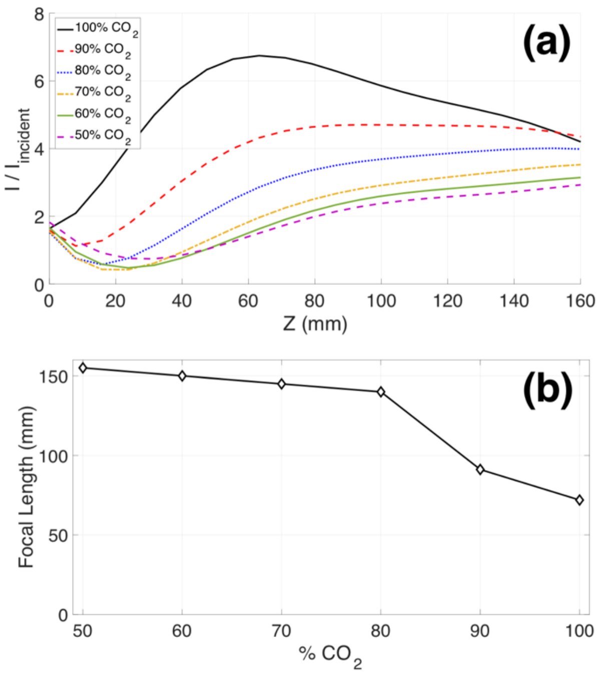

Fig. 4: (Colour on-line) (a) Longitudinal relative sound intensity distributions of cuboid lens. (b) Focal distance as a function of CO_2 percentage.

It could be noted from Figure 5 that simulations and experimental results present a good agreement so it enables us to validate simulated result presented.

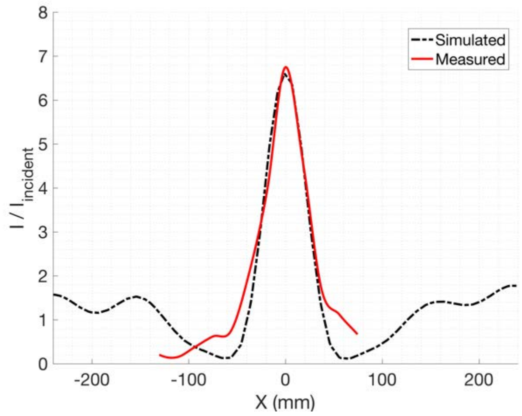

Fig. 5: (Colour on-line) Comparison of measured and simulated transverse relative sound intensity distributions in the focus.

Conclusions. – In conclusion, it has been shown that by decreasing the percentage of CO_2 inside the cuboid, the sound speed of gas medium increases so that the deformation of the wavefront, which is responsible for the focalization, is smaller due to the lower relative sound speed with respect to the air outside the cuboid. This fact causes a decrease in intensity at the focus and a greater focal distance.

This conclusion does not contradict the general physical laws, but is not obvious for lenses with flat surfaces and dimensions comparable with the wavelength. This device is believed to have potential applications as a flat low cost acoustic lens.

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