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Fresnel Zone Plate lenses present a high capacity to generate focus spot. In acoustics, these ultrasound lenses can be used in both HIFU and imaging systems. One of the limitations of classical Fresnel Zone Plates is the difficulty to control either the lateral lobes or the length of the focus. These focal geometric parameters are directly related to lateral resolution and depth of focus, respectively. In this work, we study the introduction of a new free parameter in the design of Fresnel lenses called reference radius/reference phase [1-2], which in some cases is equivalent to the introduction of a pupil mask in the lens. The ultrasound beamforming can be manipulated by means of this free parameter. The election of the appropriate value for the reference radius allows the lateral resolution improvement by reducing the lateral lobes or the expansion of the focus. This last effect is achieved through the generation of quasi-Bessel beams due to transformation of spherical waves into quasi-conic waves by means of apodization of the central part of the lens [3-5]. Therefore, the characteristics of the focus can be modified without changing the topology of the lens by using a pupil mask.

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I. Introduction

Focusing and, in general wave modulation, is a hot research topic in many areas of physics and engineering due to its multiple applications. Lenses are devices that achieve, through different physical phenomena such as refraction or diffraction, beam focusing and modulating effects. In the acoustic field, lenses have been developed for different areas such as biomedicine, engineering, and industry. One of the reasons why lenses are used in different fields is to reduce costs, since the use of lenses prevents the manufacture of new transducers [6-15]. Due to the interest that these lenses have gained, their design and improvement is currently a research subject. In such a way, ultrasonic sensors are very varied ranging from their use to verify trees in poor condition, being a non-invasive technique [16], even to produce microfluidic movement by means of slightly focused acoustic waves [17]. Zone Plates are one of these devices based on both refraction and diffraction mechanisms, which can achieve wave focusing. Acoustic lenses based on constructive interferences of diffracted fields, such as Fractal Lenses or Fresnel Zone Plates (FZP), are a good alternative to refractive lenses. FZP lenses have advantages in situations where size, weight, system complexity and fabrication are important [18,19]. The classic FZPs that are implemented alternating transparent to opaque Fresnel zones are called Soret Zone Plates (SZP) [20]. This work is focused on this type of Fresnel's lenses.
Although the diffraction of the acoustic field produce a maximum pressure field in the axis, the focal point shows some miss-definition due to the existence of secondary lobes [21,22]. In such a way, the relationship between the main and secondary lobes, known as Side Lobe Level (SLL), is one of the main problems that SZPs can exhibit [23]. This parameter is related with lateral resolution. Moreover, relative small Depth of Focus (DoF) is other of the problems that SZP lenses have. To increase the depth of focus and spatial resolution many papers investigated so-called acoustic Bessel beams due to the central core spot size of the Bessel beam, which is defined from the properties of the zeros of a Bessel function. For example, with the help of an axicon, it is possible to form a Bessel beam of zero order [24], whose central spot diameter at the half-wave intensity (Full Width at Half Maximum, FWHM) is equal to:

$$FWHM = 0.36/NA$$

where NA is the numerical aperture.

In this work, we study the introduction of a new free parameter in the design of Fresnel lenses called reference radius/reference phase [1-2], which in some cases is equivalent to the introduction of a pupil mask in the lens. The election of the appropriate value for the reference radius allows the lateral resolution improvement by reducing the lateral lobes or the expansion of the focus. This last effect is achieved through the generation of quasi-Bessel beams due to transformation of spherical waves into quasi-conic waves by means of apodization of the central part of the lens [3-5]. Therefore, the characteristics of the focus can be modified without changing the topology of the lens by using a pupil mask.

II. Methodology

To simplify the problem without loss of generality, geometrical optics interpretation is considered (Fig. 1).As it well-known, a binary SZP lens consists of concentric ring, which can be treated as a quasi-periodic grating with different local grating constants at different radii. For point focusing, the normal incident wave is diffracted towards the designed focal point by these local gratings. The diffraction angles change in order to ensure the formation of a focal spot (Fig. 1a). In this content SZP with pupil mask (PSZP) may be also considered as ring gratings because of the widths of transparent zones are almost constant while the pupil is blocking a central part of SZP. Thus, the local gratings diffract the incident waves towards different points on the optical axis with a small range of diffraction angle (Fig. 1b).

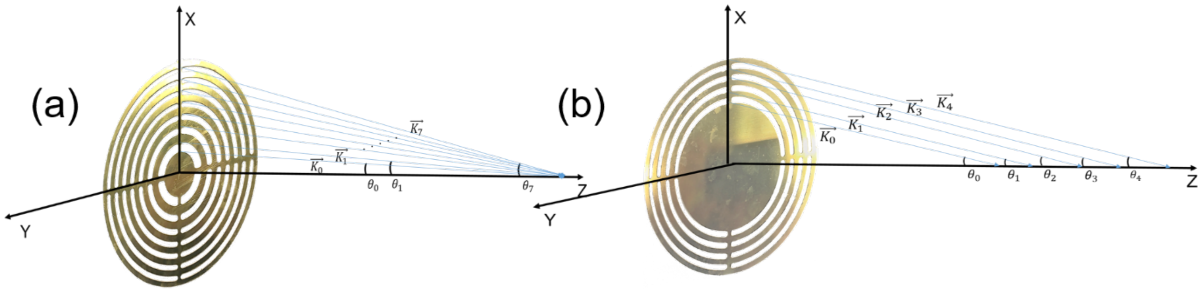

Figure1. Ray-tracing for Soret Zone Plate (SZP) (a) and Pupil Mask Soret Zone Plate PSZP (b).

For axicon [26] due to the diffraction angle (θ) of the ring grating and the grating period (P) are related by the Bragg's law: $P\cdot\sin(\theta) = m\lambda$, where m is the diffraction order and λ is the incident wavelength of acoustic wave, it produces Bessel beam. In the case of SZP with pupil mask, whose local periods P_i are not regular, we block those rings that cannot be considered as periodic. Then we may write that local $P_i=\Delta r_i$, where r_i is a width of i-th transparent zone and due to r_i is almost constant, and thus diffraction angles (θ_i) are also almost constant, such pupil-masked SZP will produce a quasi-Bessel beams. When choosing the size of the pupil mask there is a compromise. On the one hand, the period and size of the slits should be as close to the periodic as possible. On the other hand, it is necessary to leave as many zones as possible on a fixed diameter of the lens in order to provide a sufficient length of focus. According with [4] we settled on the criterion when the differences between neighboring zone width is less than $\lambda/5$. To verify the above-mentioned idea and simulate the acoustic pressure distribution in axisymmetric models of SZP we used the commercial software COMSOL Multiphysics with FEM method [25]. Experimental measurements have been carried out in order to demonstrate the focusing capabilities of SZP and PSZP. The experimental set-up consists of an underwater 3D positioning system with a spatial resolution of 1x1x1 mm^3. The ultrasound signal is generated using a Panametrics Pulser and then emitted using an Imasonic piston transducer with 30 mm of active diameter and a central frequency of 250 kHz. A needle hydrophone from Precision Acoustics Ltd. with 1.5 mm of diameter is employed as receiver. The received signal is preamplifier and then digitized using a programmable digital oscilloscope from Pico Technology. Underwater transmission is considered with typical water values of sound speed propagation (v=1500 m/s) and density (ρ=1000 kg/m^3). Design frequency (f) is 250 kHz, therefore wavelength (λ) is 6 mm. Lenses were defined full rigid considering Neumann condition. Mesh geometry was selected in triangles with minimum element size of $\lambda/14$ and maximum element size of $\lambda/8$ to prevent numerical dispersion.

III. Results and discussion

The SZP lenses with high NA = 2.5 was selected (the NA is determined by both the diameter of the lens and the specified primary focal length as NA = D/2F) due to focusing of this device with F = 4.5 leads to a very compact beam with a short working distance. It could be noted that we cannot use the well-known equations for NA due to small focal distance where the paraxial approximations are not valid. Analysis of the simulations shown that the focused field in the cases of PSZP (Fig. 2b) instead of classical SZP (Fig. 2a) has a characteristic structure for quasi-Bessel beams with intensity profiles that closely resemble the ideal J_0^2 transverse intensity distribution of Bessel beams. The values of FWHMs and DoFs for these acoustical lenses are shown in Table I.

Table I. DoF at -3dB and FWHM, for SZP, PSZP and Bessel Beam

	SZP	PSZP	BESSEL BEAM
FWHM	0.84	0.64	0.64
DoF	2.84	5.94	-

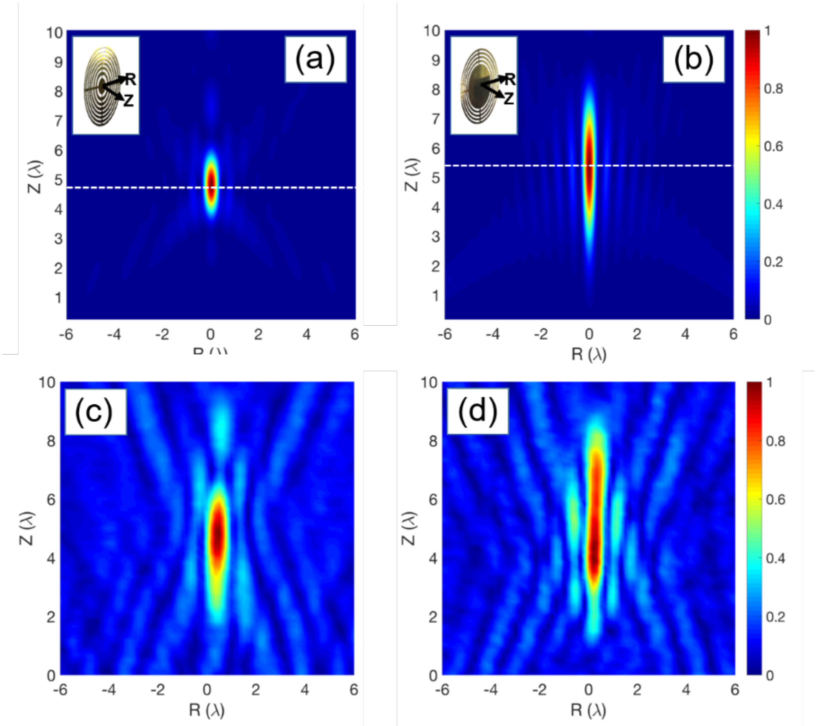

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Figure 2. Self-normalized intensity maps to the maximum with the R- and the Z-axis normalized to *l* for (**a**) a Soret Zone Plate (SZP) and (**b**) an SZP with amplitude Pupil mask (PSZP). (**c**) and (**d**) correspond to experimental results for SZP and PSZP respectively.

It can be observed from Figure 2 a,b that the numerical results for SZP and PSZP lenses present focusing profiles with different focal lengths and shapes. As expected, the PSZP has a more extensive focus area (larger DoF) than the SZP. Figure 2 c, d shows the experimental self-normalized intensity maps for the SZP lens (Figure 2 c) and the PSZP lens (Figure 2d). It can be seen that the pupil mask effect elongated the focus due to the diffraction grating lens behavior. In the SZP lens, as shown in Figure 2c, the focus was located at the designed focal length. In the PSZP case, the maximum energy was located at the same focal length as in the SZP case, but the energy was distributed along the longitudinal axis with a needle shape. The PSZP focused beam was also narrowed with respect to the SZP case.

IV. Conclusion

In this paper, it is shown that the focusing properties of an acoustic Zone Plate can be controlled without changing the structure of the zones by introducing an amplitude pupil mask. In this case, diffraction by a quasi-periodic ring lattice formed by peripheral Fresnel zones leads to the formation of an elongated focus corresponding to the structure of a quasi-Bessel beam. The depth of focus is determined by both the size of the pupil mask and the diameter of the acoustic lens. Therefore, circular gratings based on pupil-masked SZP, will enable an intense beam and an extended focus. It is possible to control the depth of focus of the acoustic Soret lens, quickly, by dynamically changing only the size of the amplitude pupil mask. Experimental verification shows that the depth of field increases to 1.63 times and resolution increase to 1.2

times (with minimal beam waist about of 0.67λ and depth of focus about 5.72λ). Such systems can find wide application in nondestructive devices, acoustic microscopy, imaging systems and control of nano and microparticles. The extremely easy generation of these beams using pupil binary mask proposed here can handle high wave powers, thus is particularly suitable for applications in plasma channel generation, nonlinear optics, and X-ray or microwave beam manipulation. Moreover, this approach can also be directly applied to light and matter waves.

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