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Broadband aberration-free focusing reflector for acoustic waves

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ABSTRACT

An aberration-free focusing reflector (AFR) for acoustic waves is proposed with the aim to eliminate spherical aberration and coma simultaneously. Meanwhile, the AFR can focus acoustic waves with low dispersion in a wide frequency range of 14–50 kHz. The broadband aberration-free focusing effect is originated from an elliptical reflection phase gradient profile, which is achieved by milling different depths of axisymmetric grooves on a planoconcave-like brass plate using the ray theory. Theoretical and numerical results are in good agreement. The designed AFR can find broad engineering, industrial and medical applications.

1. Introduction

Acoustic focusing lenses and reflectors with low aberrations are very useful for high focus quality fields like ultrasonic imaging, ultrasonic dicing and abolition of tissues for biomedical applications. The acoustic lenses with low aberrations have been studied early in 1960s [1,2]. In the past decades, spherical biconcave acoustic lenses [3], spherical biconvex acoustic lenses [4], bicylindrical acoustic lenses [5], aspherical plano-elliptical acoustic lenses [6], and aspherical Fresnel acoustic lenses [7] were put forward and fully studied. Results show that both spherical and aspherical lenses can remove spherical aberration in the paraxial area, and coma can be removed only in [7] with an angle no more than 10°. Meanwhile, paraboloidal reflectors [8,9] and ellipsoidal reflectors [10] without spherical aberration have also been studied a lot. However, few studies have been concerned with coma of the reflectors, which should be averted in high focus quality systems.

In recent years, researchers have made great effort to explore acoustic metasurfaces (AMS) owning to their compact planar subwavelength structure and wavefront shaping capabilities [11–21]. The AMS have promoted many applications including acoustic focusing [11–17], extraordinary refraction and reflection [18–20], noise control [21] and so on. The acoustic lenses and reflectors for focusing were mostly designed by AMS with hyperboloidal phase gradient profile. In 2016, Wu et al. proposed a reflective underwater focusing metasurface with linearly tunable focal length by milling different depths of grooves on a brass plate [11]. Wang et al. designed the AMS by using circular-holed cubic arrays with suitable hole diameters to focus acoustic waves [12]. Zhai et al. designed the AMS constructed by a combination of membranes and cavities and realized the focusing effect through changing the width of membrane [13,14]. Li et al. used the coiling-up structures to design the AMS for focusing ultrasonic or audible sound waves [15,16]. However, these AMS were limited at a given frequency or may be not effective in a broad frequency range. Moreover, the researchers cared little about the aberrations.

In this paper, we present a broadband aberration-free focusing reflector (AFR) built by a spherical planoconcave-like brass plate. The theoretical and simulated results both show that this metal reflector can focus reflected acoustic waves without spherical aberration and coma. It, meanwhile, has little reflection loss and can be applied to larger power case compared to the lens. In addition, the AFR of 3D pattern can focus acoustic waves with low dispersion in a wide frequency range of 14–50 kHz.

2. Modeling and simulations

In order to predict the focus characteristics of the AFR, a planar reflector (PR) is also estimated comparatively. The normal incidence and off-axis aberration are both studied by using the ray theory [22,23] and the third-order (Seidel) aberration theory [24,25].

2.1. Design of reflectors without spherical aberration

At the beginning of this design, the brass plates were used. The 2D reflection geometries of the PR and AFR are shown in Fig. 1. The heights of these two reflectors are both 16 cm, and the width

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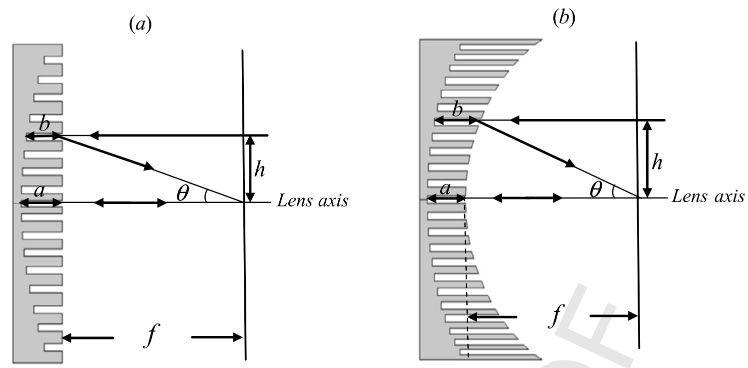

(c)

θ(deg)	b(cm)	θ (deg)	b(cm)
0	2.50	25	1.98
5	2.48	30	1.73
10	2.42	34	1.47
15	2.32	38	1.10
20	2.18		

(d)

θ(deg)	b(cm)	θ (deg)	b(cm)
0	2.50	30	3.17
5	2.52	35	3.40
10	2.58	40	3.67
15	2.67	45	3.96
20	2.80	50	4.28
25	2.97	55	4.63

Fig. 1. (*a*) Geometry of the PR and the acoustic ray (normal incidence); (*b*) Geometry of the AFR and the acoustic ray (normal incidence); (c) The depths of the grooves with θ for the PR; (d) The depths of the grooves with θ for the AFR.

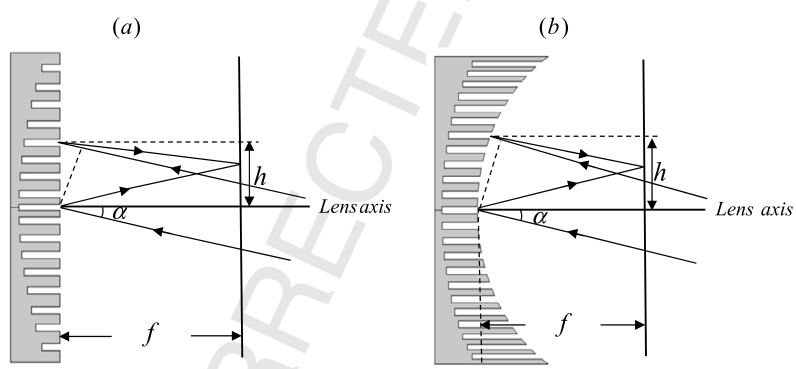

Fig. 2. (*a*) The off-axis case for the PR; (*b*) The off-axis case for the AFR.

of the PR is 3 cm. The maximum and minimum widths of the AFR are 7 cm and 3 cm, respectively. According to the ray theory, to focus acoustic rays without a spherical aberration, the reflector must satisfy the equal path principle. For the PR, it is:

$$f + 2a = f/\cos\theta + 2b, \tag{1a}$$

and for the AFR, it is:

$$f - f\cos\theta + 2a = 2b, \tag{1b}$$

where the parameter f is the focal length and it is 10 cm for both reflectors, b is the groove depth in the reflectors, a is the central groove depth, and θ is the angle between a marginal and an axial image ray.

According to the Pythagorean Theorem, as for the PR:

$$f^2 + h^2 = (f/\cos\theta)^2, \tag{2a}$$

and for the AFR:

$$(f\cos\theta)^2 + h^2 = f^2, \tag{2b}$$

where h is the height of the incidence. By solving Eq. (1a) and Eq. (2a), Eq. (3) can be obtained:

$$\frac{(b-(a+f/2))^2}{(f/2)^2} - \frac{h^2}{f^2} = 1, \tag{3}$$

and by solving Eq. (1b) and Eq. (2b), the following equation can be obtained:

$$\frac{(b+(a-f/2))^2}{(f/2)^2} + \frac{h^2}{f^2} = 1. \tag{4}$$

According to Eq. (3) and Eq. (4), the reflection phase profile is hyperbolic for the PR and elliptical for the AFR. In order to fulfill these two reflection phase profiles, different depths are chosen according to Eq. (1) and Eq. (2). The depths of the grooves with θ are shown in Fig. 1(c) and Fig. 1(d), where the widths of the grooves are 0.4 cm and appropriately adjusted at the edge of the AFR.

2.2. Off-axis aberration

The off-axis case, with distant object point or parallel rays in the paraxial area, is shown in Fig. 2. The wave path difference (WPD) between the marginal and the axial ray of the PR can be expressed by:

$$\mathrm{WPD} = h\sin\alpha + \left[f^2 + (h - f\tan\alpha)^2\right]^{\frac{1}{2}} - f\left(1+\tan^2\alpha\right)^{\frac{1}{2}} \tag{5}$$

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