Phase-Matching holographic metasurfaces for accurate acoustic image generation

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Abstract: Holographic metasurfaces can tailor acoustic wavefronts to produce arbitrary acoustic images; however, current methods are not able to accurately encode the target phase distribution. We propose a novel technique for designing the metasurface by matching the phase at the lens exit with the target phase over a whole volume.

Acoustic holograms are complex lenses that encode customized phase distributions in their structure, allowing the creation of specific acoustic pressure patterns within a medium [1]. The underlying principles of this technology are based on interference and diffraction, much like optical holograms, but applied to sound waves. This technology has proven to be highly adaptable, with a wide range of applications in areas, mainly using ultrasound [2–7]. Between them, a promising application of acoustic holograms is therapeutic ultrasound and in particular transcranial ultrasound, where holograms can compensate for phase aberrations produced by the skull and generate sharp focal spots or arbitrary acoustic images inside the human brain [2].

In current hologram design techniques, the target field is defined along a transverse plane, and the lenses are designed to match the phase of the field in this plane. This approach is ideal when the lens is a perfect flat metasurface. However, its implementation using phase plate lenses often fails to reproduce the desired phase as a result of nonplane wave propagation, refraction, and diffraction effects.

In this work, we propose a novel approach called *phase matching*, where the field is acquired in a volume rather than a plane, and the phase at the lens exit is aligned with the target phase throughout the volume. The proposed method is validated through analytical solutions, simulations, and experiments. First, a single focal lens is designed using a 1.1-MHz circular 50-mm aperture source and various 3D printing materials and a parametric study of its focusing performance is conducted. Second, several complex acoustic images at different depths are generated, with their structural similarity index measure (SSIM) evaluated.

For simple focused beams, our method produces sharper focal spots with greater focusing gain. These focal spots are closer to the diffraction-limited estimations. For materials with a refractive index lower than one, both methods produce hyperbolic phase profiles, but only the phase-matching approach provides the optimal solution as seen in Fig. 1(a-b). For low f-numbers, phase matching outperforms classical methods, while for moderately focused beams, both approaches converge. Furthermore, we observe that the structural similarity index measure (SSIM) of complex acoustic images generated at shorter distances is higher with the proposed method, particularly for short focal lengths as shown in Fig. 1(c).

Phase-matching holograms enable precise synthesis of the target field's phase at the lens exit, surpassing traditional acoustic hologram design methods. This approach is particularly suited for emerging therapeutic ultrasound applications that require precise acoustic beam control, especially in cases where full-wave simulations are computationally intensive to be used for optimization methods.

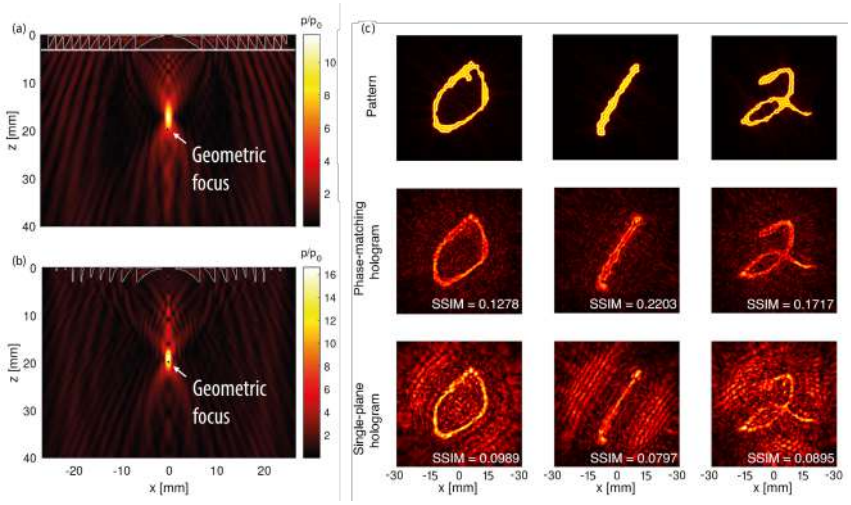


Figure 1: (a) Focal lens obtained through traditional methods. (b) Focal Lens obtained through phase-matching approach. (c) Acoustic patterns obtained using phase-matching and traditional (single-plane) methods

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