

Holographic mirrors for spatial ultrasound modulation in contactless acoustic energy transfer systems

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ABSTRACT

This work introduces and investigates a flat acoustic mirror capable of efficiently manipulating a wavefront and creating an arbitrary pressure pattern in a target plane using the sound reflection phenomenon. The mirror is a metallic holographic lens that performs as a spatial ultrasound modulator by introducing a relative phase shift to the reflected wavefront. The phase-shifting lens is designed using an iterative angular spectrum algorithm and 3D-printed from powdered aluminum through direct metal laser melting. The lens's capabilities to construct diffraction-limited complex pressure patterns under water are tested numerically and experimentally. The proposed holographic mirror design can drive immense improvements in applications involving contactless acoustic energy transfer, which is investigated in this Letter.

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The intricate acoustic wave manipulation and focusing have gained significant attention due to their broad applications in the fields of medical ultrasound,^{1–5} contactless acoustic energy transfer (AET),^{6–10} nondestructive evaluation (NDE),^{11,12} and sensing. In the scope of reflected acoustic wave tailoring, acoustic metamaterials have shown significant capabilities to manipulate reflected waves such as wavefront transformation,^{13,14} extraordinary sound reflection,¹⁵ and amplitude and phase modulation.¹⁶ Using an ultrathin reflective metasurface based on locally resonant Helmholtz-like elements, Qi and Assouar¹⁷ showed theoretically that a metasurface can confine acoustic intensity to about ten times the intensity of a free plane wave field. Similar acoustic focusing effects have also been realized by coiling up space¹⁸ and by using labyrinthine units.¹⁹ Still, most of these capabilities have been demonstrated for a range of frequencies between 1 and 17 kHz. Since metamaterials are made of labyrinths or arrays of unit cells of sub-wavelength size,^{20,21} extending their implementation to the ultrasonic range is challenging and requires complicated fabrication techniques.

Recently, Prat-Camps *et al.*²² introduced a manually reconfigurable reflective phase modulation device to manipulate ultrasonic waves. The reflective device consisted of a rectangular array of variable depth

piston waveguides. One distinct advantage of such a device is the real-time control over the sound field, whereby the phase delay can be continuously modified because each piston can be separately controlled. The experiments were performed in air at an operating frequency of 40 kHz. We hypothesize that extending such a device to the MHz range can make it very complex and expensive. Also, electronically controlling each piston by an array of microstepper motors or solenoid magnets adds more complications for underwater operation. Despite the intriguing features provided by artificially structured acoustical materials, the spatial control over the reflected wavefront in ultrasound frequencies and in water to generate arbitrary and elaborate wave fields, i.e., multifocal point beamforming, remains unexplored. In contrast, passive acoustic mirrors have been used to reflect and spatially focus sound waves. These mirrors are based on specific curved paraboloid or ellipsoid shapes that bend the sound beams for acoustic source localization.^{23,24} Melde *et al.*²⁵ demonstrated a 3D-printed lens for levitating fluid droplets and solid particles in the air. The lens was designed to generate a standing wave field with multiple transverse traps in a cavity geometry.

Using acoustic holographic techniques, we report on the theoretical design, numerical simulation, and experimental demonstration of a

3D-printed metallic holographic acoustic mirror (HAM). For comparison purposes, 3D-printing of the metallic lens with a lateral resolution of $304\text{-}\mu\text{m}$ ²⁶ can yield approximately 68 000 acoustic pixels compared to the 1024 elements in the design of Ref. 22. The higher pixel density enables finer wave manipulation up to 2.3 MHz (with a pixel size of $\lambda/2$, where λ is the wavelength). The HAM acts as a spatial sound modulator. Because the phase shift imposed by the mirror is depending on the wavelength, the operation is narrow-band around the design frequency. As schematically shown in Fig. 1, the HAM reflects an acoustic wave generated by a cylindrical acoustic transducer located between itself and the target plane. The unique thickness map of the HAM introduces a phase shift distribution to the reflected wavefront that propagates downstream and generates the desired pressure pattern at the target plane. The configuration, shown in Fig. 1, utilizes the reflected acoustic energy that would have been otherwise wasted. As such, higher power outputs can be achieved due to the more efficient and selective energy transfer, which is especially attractive for acoustic energy transfer and sensing applications.

To design the holographic mirror, we first compute the pressure phase distribution as required at the mirror plane $z = Z_m$ to produce the desired pressure pattern at the target plane, $z = Z_t$, as shown in Fig. 1(b). The phase information is then used to develop the thickness map of the HAM, which is then fabricated using direct metal laser melting. We use the iterative angular spectrum algorithm (IASA)^{25,27} to determine the desired phase distribution. IASA is a modification of the Gerchberg-Saxton algorithm,²⁸ which was first introduced for optics applications and has been used for computer-generated holography. The steps of the algorithm for designing the holographic mirror are summarized in the [supplementary material](#) (see Fig. S1 in the [supplementary material](#)).

The first step in designing the mirror is to determine the reflected complex pressure. Due to the difficulty of experimentally measuring

the reflected pressure and evaluating errors at the mirror plane, we base the mirror design for under water implementation on simulations using COMSOL Multiphysics 5.4. The transmitter disk parameters used in the simulations were obtained from an experimental parameter identification based on electromechanical impedance and acoustic pressure measurement data (see Figs. S2 and S3, and disk parameters in the [supplementary material](#)). These covered a broad range that included the resonant frequency at 780 kHz. The size of the transmitter disk was chosen based on the acoustic field aperture and the resonant frequency of the disk. The simulation analysis was then carried out using the acoustic-piezoelectric interaction and the frequency domain acoustic-electro-elastic multiphysics interface. The domains were meshed with tetrahedral elements with a maximum size of $\lambda/6$. A spherical radiation boundary condition was applied to the external boundaries. The reflected pressure was calculated using $p_{\text{ref}} = p_{\text{tot}} - p_{\text{inc}}$, where p_{inc} and p_{tot} are, respectively, the incident pressure generated by the piezoelectric disk and total pressure, both at the mirror plane. The simulation was first performed in the absence of the mirror to obtain the incident pressure that was also verified experimentally (see Fig. S4 in the [supplementary material](#)). The mirror was then placed in the computational domain to obtain the total pressure. The simulated mirror had the following elastic properties, a modulus of elasticity of 68.3 GPa, a density of 2.67 g/cm^3 , and Poisson's ratio of 0.35. Subtracting the two complex pressures resulted in the reflected pressure at the mirror plane, which was then used as an input to the iterative algorithm. The metallic holographic mirror was 3D-printed with powdered aluminum (AlSi10Mg) by Stratasys using direct metal laser melting (DMLM) with a theoretical printing resolution of $20\text{ }\mu\text{m}$ in the z -direction.²⁶ The material of the mirror was chosen to have high impedance mismatch with water to achieve efficient reflection. The printed mirrors are flat and disk-shaped with a diameter of 90 mm and a nominal thickness of 10 mm. After fabrication, the surface was treated with media blasting to get a smoother surface and consequently less diffusion in the reflected wavefront. The process provides a satin finish of approximately $2.5\text{--}6\text{ }\mu\text{m}$ Ra surface roughness,²⁶ where Ra is the arithmetic average of the surface roughness profile.²⁹ For the present study, the typical surface roughness is much smaller than the wavelength and, as such, the scattering is comparable to that of a smooth surface.^{30,31}

Two sets of experiments were performed to demonstrate the use of holographic mirrors. In the first set, the mirror, shown in Fig. 2(a), was designed to generate the flower-shaped pressure pattern presented in Fig. 1(b) in a target plane 70 mm away from the mirror in the z -direction at an operating frequency of 780 kHz. Since the acoustic field constructed by the mirror is diffraction-limited, the location of the target plane should be at a distance in which the minimum feature size of the pattern can be resolved. The corresponding thickness map for this mirror, as determined from the simulations and algorithm, is shown in Fig. 2(c). This pattern was chosen to demonstrate the capability of the reflective mirror in generating elaborate pressure fields. The mirror was illuminated by an acoustic field generated by a piezoelectric disk having a diameter of 9 mm and a thickness of 3 mm and placed 35 mm away from the mirror. The location of the mirror with respect to the source should be at the distance far enough to avoid the multiple reflections from the mirror and the cylindrical source surface that results in the formation of standing waves.⁷ The disk was fixed by a 3D printed holder that was printed using VeroClear, a transparent

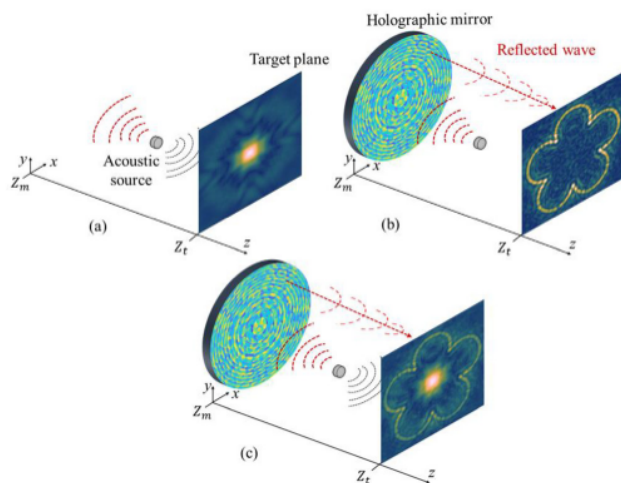


FIG. 1. Schematic representation of the acoustic pressure distribution in the target plane at $z = Z_t$, (a) when there is no holographic mirror, i.e., forwarded incident wave, and (b) in the presence of the reflective mirror at $z = Z_m$, i.e., guided reflective wave. The mirror reflects the incoming acoustic wave from the cylindrical acoustic source and modulates its phase to construct the desired pressure pattern (flower shape) at the target plane. (c) Total acoustic pressure, i.e., forward and reflected fields at the target plane.

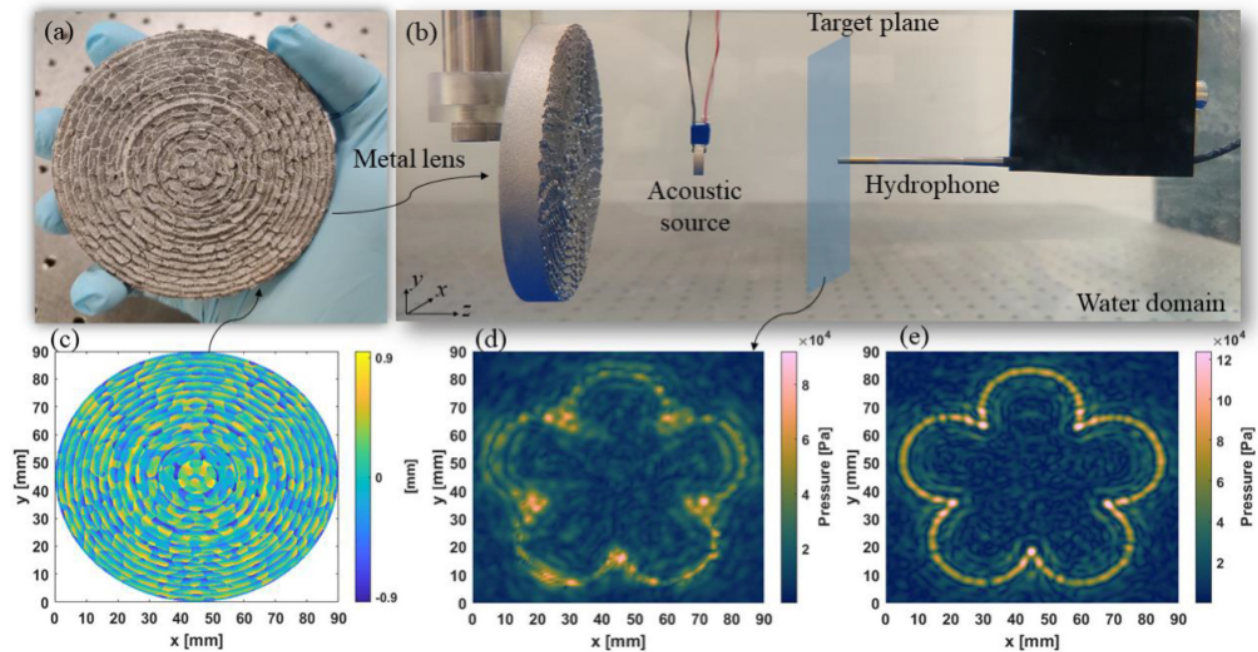


FIG. 2. (a) Printed holographic acoustic mirror (lens), (b) the experimental setup with the printed mirror located at 35 mm from the acoustic source, hydrophone, and piezoelectric cylindrical acoustic source, and (c) the lens thickness map. (d) Experimentally measured pressure amplitude distribution at the target plane at 780 kHz. (e) Theoretical pressure amplitude distribution at the target plane. The target plane is located at a 70 mm distance from the mirror in the z -direction.

photopolymer material. The transmitter was excited by a sinusoidal pulse signal (25 cycles) with an actuation amplitude of 103 V that is provided by a signal generator (Keysight 33500B) and an amplifier (Electronics and Innovation A075). The actuation amplitude was chosen in order to realize appreciable pressure amplitudes at the target plane.

The mirror and the acoustic transmitter were mounted in degassed and de-ionized water in a tank that was partially covered with Aptflex F28 acoustic absorbing sheets manufactured by Precision Acoustics, Ltd. The pressure field on a specified target plane was mapped with the ONDA HNR-0500 needle hydrophone attached to a custom-built in-house 3D positioning system, as shown in Fig. 2(b). The uncertainty in the sensitivity of the hydrophone (calibration factor) was defined within ± 1.5 dB ($\approx 19\%$). A spatial sampling resolution of $\lambda/2$ was employed to avoid aliasing. The measured signal from the hydrophone was sampled and digitized by a Tektronix TBS2104 oscilloscope and averaged 64 times to increase the signal-to-noise ratio. To eliminate the effect of any DC bias and higher frequency noises, the signal was post-processed using MATLAB by performing an FFT on the time series. The amplitude and phase corresponding to the operating frequency were obtained. A MATLAB program was used to control the positioning system and triggering of the function generator. The obtained voltage amplitude was then converted into acoustic pressure according to the calibration factor provided by the manufacturer. To map the reflected pressure at the target plane without the interference of the incident wave generated from the other side of the transducer, we exploited the time delay caused by the difference in the propagation distances. The measurements were carried out

when the reflected pulse was arriving at the target plane sufficiently long after the departure of the incident pulse.

Figure 2(d) shows the experimentally measured pressure amplitude distribution at the target plane. By comparing it with the theoretical prediction, shown in Fig. 2(e), we note that a good agreement is achieved in the general pattern of the target and that the locations of high-pressure points in the experiment match closely those in the theoretical prediction. The results also show that the experimental pressure pattern is not as clean as the theoretical prediction and that there is a difference of less than 25% in the pressure amplitude. These errors can be attributed to misalignments, uncertainties in hydrophone sensitivity, fabrication imperfections, and material inhomogeneities.

In the second set of experiments, we considered a pattern with four uniform focal areas defined by circles with a diameter of 15 mm, as shown in Fig. 3(a). The experimental setup with the printed mirror, hydrophone, and piezoelectric cylindrical acoustic source is similar to the setup presented in Fig. 2(b). The corresponding phase distribution and the thickness map of the holographic mirror are presented in Figs. 3(b) and 3(c), respectively. The experimentally measured and the theoretical prediction of the pressure pattern are shown in Fig. 3(d) and Fig. 3(e), respectively, which show a good agreement. Figure 3(f) shows the total acoustic pressure, i.e., forward and reflected fields at the target plane. The total pressure was experimentally obtained by sending long-pulsed signals and measuring the pressure when both the reflected and forward waves were present at the target plane.

To measure the overall reconstruction quality of the experimental results, we implement a metric equivalent to the diffraction efficiency in optics.^{32,33} The reconstruction efficiency is obtained by relating the

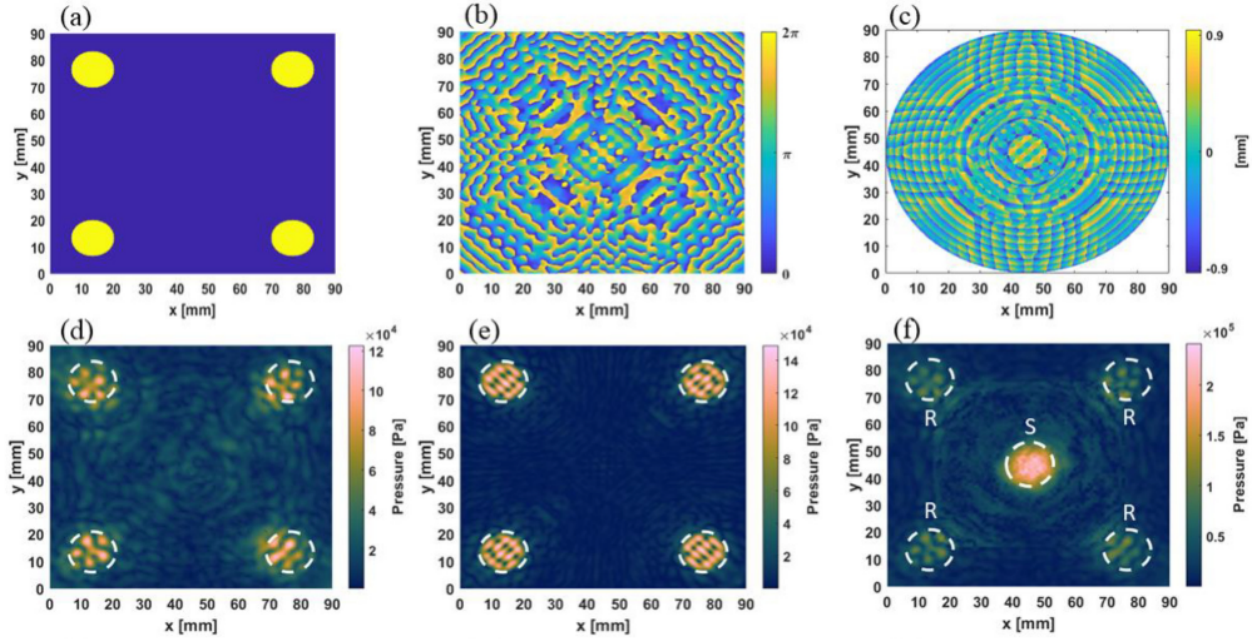


FIG. 3. (a) The desired amplitude map at the target plane. (b) Calculated phase distribution at the mirror plane at 780 kHz. (c) The mirror thickness map. (d) Experimentally measured reflected pressure amplitude distribution at the target plane. (e) Theoretical pressure amplitude distribution at the target plane. The target plane is located at a 70 mm distance from the mirror in the z-direction. The dashed circles in (d) and (e) represent the desired locations of the receivers in the target plane, which is of interest for the AET applications. (f) Experimentally measured total pressure amplitude (i.e., forward and reflected) fields at the target plane.

experimentally measured acoustic power in the focal non-zero regions of the binary target pattern to the total acoustic power in the whole target plane. The plane-traveling wave is assumed in the calculations of the acoustic intensity and power. The acoustic intensity of each sampling point is calculated from the experimental pressure amplitudes as

$$I(x, y, Z_t) = \frac{p(x, y, Z_t)^2}{2\rho c}, \quad (1)$$

while the acoustic power at the target plane, Π , is the summation of all intensities over the sampling points multiplied by their corresponding areas

$$\Pi = A_s \sum I(x, y, Z_t). \quad (2)$$

Because the spatial sampling resolution Δd_s is constant along with the x and y coordinates (i.e., $\Delta d_s = \Delta x_s = \Delta y_s$), the sampling area is defined as $A_s = \Delta d_s^2$. Finally, the reconstruction efficiency is expressed as

$$\eta = \frac{\Pi_{focal}}{\Pi_{total}} = \frac{\sum p_{focal}^2(x, y, Z_t)}{\sum p^2(x, y, Z_t)}, \quad (3)$$

where $p_{focal}(x, y, Z_t)$ and Π_{focal} are the acoustic pressure distribution and the acoustic power in the focal regions in the target plane, respectively, and Π_{total} is the total acoustic power in the target plane. The total acoustic power is due to the constructive and destructive interference between the forward and reflected pressure fields. The theoretical efficiency was calculated to be 61%, while the experimental efficiency

is 34%. The results reveal that the experimental pattern did not align perfectly with the desired pattern. We attribute this inconsistency to the misalignments (see Fig. S5 in the [supplementary material](#)). To quantify the errors and evaluate the sensitivity of the pressure at the target plane to misalignments, a set of numerical simulations was performed. The results show that lateral misalignments have a more significant effect on reconstruction efficiency compared to axial misalignments. The efficiency drops by 53% for a lateral shift of 2.25 mm and by 5% for the same shift in the axial direction. It is noteworthy to mention that relaxing the alignment criteria and considering a larger target area, e.g., extending the target circle radius by 75%, will increase the experimental reconstruction efficiency from 34% to 56% (see Fig. S6 in the [supplementary material](#)).

By localizing the acoustic energy to desired focal areas, efficient and selective power transfer can be achieved. For instance, the circles in Fig. 3(f) can be considered to represent locations of piezoelectric receivers operating in the 33-mode with the fundamental resonant frequency of 780 kHz and connected to an external load resistance. Shahab *et al.*⁸ derived the coupled electro-elastic equations for fluid-loaded longitudinal vibrations of the receivers assuming linear piezoelectricity and neglecting elastic coupling and dissipative nonlinearities and showed that the electrical power-output response, E_{out} , is proportional to the input acoustic power on the receivers at the target plane, i.e., $E_{out} \propto \Pi_{focal}$ (see Eq. S7 in the [supplementary material](#)). Using that analysis, employing the mirror in the AET setup leads to a 2860% increase in the power output for receivers R in Fig. 3(f) and 146% increase for the total electrical power output in the target plane (receivers R and S). The focal acoustic power imposed on the receivers

TABLE I. Focal acoustic power and electrical power output in AET.

	Receivers R	Receiver S	All receivers
Without HAM Π_{focal} [W]	0.0066	1.5944	1.6208
With HAM Π_{focal} [W]	0.1890	1.6011	2.3571
E_{out} (with HAM)/ E_{out} (without HAM)	28.6	1	1.46

R and S are presented in Table I. The ratio of the electrical power output from the receivers, E_{out} , with HAM to the case of without HAM, is also presented.

We demonstrated the use of a 3D-printed metallic holographic acoustic mirror for the manipulation of reflected ultrasonic waves under water, generated by a single acoustic transmitter. Two different flat acoustic mirrors were designed using IASA, fabricated, and experimentally tested. The capabilities of the mirrors for spatial complex pressure patterning and multifocal point wave focusing were evaluated. We envision that the mirroring concept has the potential to extend the realm of critical applications that employ acoustic manipulation of reflective waves. Notably, the ability to focus sound on multifocal areas with just a single acoustic source is desirable for AET-based wireless powering and communication in sensing networks. This configuration allows the utilization of both incident and reflected acoustic energy and increasing the total acoustic power available for receivers in AET systems. By compensating for the aberrations using phase conjugation and time-reversal techniques, wave patterning through aberrating layers using acoustic holograms is possible and has been shown in medical applications.^{3,4} Another interesting concept is integrating this reflective mirror with the transmission acoustic holograms for phase and amplitude modulation.³⁴ If needed the forward wave can also be patterned by using a transmission hologram on the other side of the transmitter disk in conjunction with the reflective mirror. Thus, the reflected and forward wave can be patterned to different regions of interest achieving a very efficient AET system.

See the [supplementary material](#) for the summary of the IASA algorithm, experimental verification of the COMSOL simulations, and further misalignment and error analysis.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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