

# Design of 3D Hologram Emitting Optical Phased Arrays

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**Abstract:** We demonstrate the design of optical phased arrays that emit 3D holograms. The design concept utilizes back propagation of desired image planes superimposed at the phased array. Improvements are shown utilizing random curved phase fronts.

**OCIS codes:** (110.5100) Phase-array imaging systems; (090.2890) Holographic optical elements.

## 1. Introduction

Optical phased arrays have garnered a great deal of research attention due to their potential in communications, imaging, and detection. Recent development in the field has shown optical phased arrays can emit 2D patterns and continuously steer in one dimension [1, 2]. Currently, in microwave phased antenna arrays, high resolution is achieved at the expense of size, power, and cost. These drawbacks can be resolved by moving into the optical domain, since it maintains high resolution due to a large array size coupled with small optical wavelength [3]. The next step beyond 1D and 2D work is finding a way to extend these optical arrays to be able to tackle issues requiring 3D imaging. The previous 2D emitting phased arrays have produced outputs in the far field, which only allows for a single plane of focus, limiting it to 2D. The near field, on the other hand, allows for multiple patterns to come into focus at different projection distances, creating the framework for generating a 3D hologram. Digital holography techniques can be used to design phased arrays that generate 3D holograms, expanding their potential. In the past, digital binary holograms have been synthesized by superimposing Fourier transforms of output image planes [4]. In the biomedical field, digital 3D holography has shown the ability to detect more information than traditional radio graphs and CT images [5]. Digital holography also opens the possibility for 3D displays and TVs without requiring specialized glasses [6-8].

In this paper, we present a design technique that attempts to combine the 2D emitting phased array concept with digital holography in order to generate phased arrays with the capability to emit arbitrary 3D patterns in the near field. This is accomplished by back propagating desired output planes by using Fresnel diffraction to achieve a single electric field realizable by a phased array. This phased array will then emit our 3D pattern when forward propagated.

## 2. Phased Array Design

Fig. 1(a) shows a diagram of a phased array that is being synthesized consisting of a matrix of 128x128 antennas operating at a wavelength of 1550nm. The amplitude and phase of each antenna is set by an evanescent coupler and modifying the path length of the waveguide. A pitch of 9 $\mu$ m is used to give a total area of 1.2x1.2mm. This large area and number of antennas is critical to achieving a large hologram with high resolution.

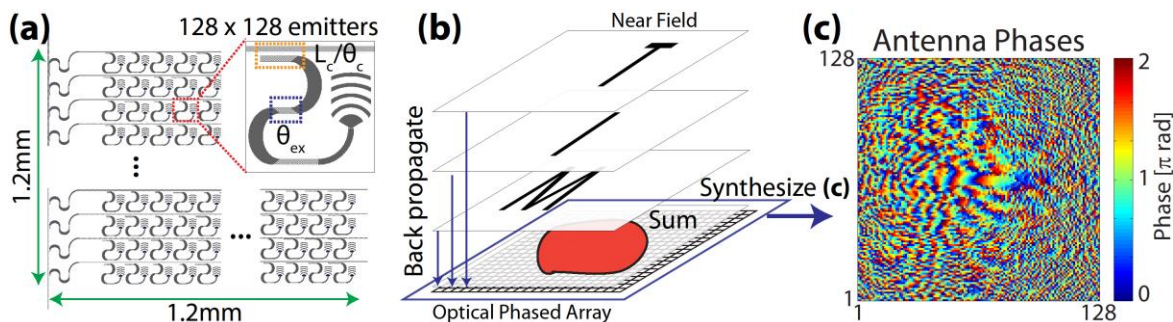


Fig. 1. (a) System overview of synthesized and simulated phased array. (b) Concept of 3D hologram design technique by back propagation of MIT logo. (c) Synthesized phase distribution for the MIT example. An amplitude distribution is also generated, but not shown.

Our 3D hologram design technique proposes that we can calculate the needed individual phase and amplitude of each antenna by back propagating multiple desired electric field distributions that mimic the planes of a 3D image. Each desired plane is at a different vertical distance from the phased array and is back propagated individually to a common plane located at the phased array. The results of these back propagations are summed into a single electric

field as depicted in Fig. 1(b). The electric field is discretized into a 128x128 point matrix, with each point corresponding to an antenna, and the phase and amplitude is extracted to synthesize the needed parameters for the phased array antennas. By ensuring these parameters for each antenna, the phased array will emit the total summed field. If the emitted electric field is now forward propagated, each of the original desired planes in the 3D space will be approximated, though each plane will not be exact because of the discretization of the field and the contributions from the other output planes. This back propagation approximates the capture of a hologram using light propagation as done in digital holography. To simulate the electric field in this step, we use the full Fresnel diffraction equation for each desired plane:

$$E(x, y; z = 0) = E(x, y; z = z_i) * \left[ \left( \frac{-jz_i}{\lambda(z_i^2 + x^2 + y^2)} \right) \left( e^{sign(z_i)jk\sqrt{z_i^2 + x^2 + y^2}} \right) \right] \quad (1)$$

where  $x$  and  $y$  are the dimensions along the plane made by the phased array and  $z$  is the optical axis.  $z = 0$  is defined to be located at the phased array and  $z = z_i$  is the location of the  $i^{\text{th}}$  desired plane. In this equation, we are convolving  $E(x, y; z = z_i)$ , the desired output plane, with the (back propagating) Fresnel diffraction impulse response to calculate  $E(x, y; z = 0)$ , the corresponding electric field at the phased array, required to generate the desired output plane. The  $E(x, y; z = 0)$  is calculated for each desired plane of the output and then are superimposed to generate the electric field that our phased array will emit as shown in Fig. 1(b). Fig. 1(c) shows an example of the phase generated using this method for a 3D hologram that consists of the MIT logo where each letter is at a different  $z_i$ .

Synthesized amplitude and phase distributions are implemented into the design by carefully designing both row couplers seen along the left side of Fig. 1(a), that couple optical power into each row of the phased array, and unit couplers of each antenna in order to route the proper amount of power to each unit cell. A system of equations is generated with the constraint of having no extra power loss at the ends of the columns and rows to solve for the needed coupling coefficients. 3D finite-difference time-domain (FDTD) simulations of evanescent couplers were run with varying gap and coupler lengths seen in Fig. 2(a). The three gaps shown in Fig. 2(b) cover a range of coupler power coefficients ranging from 0.011% to 82.5%, which covers the dynamic range of coupling coefficients required to synthesize our desired phase arrays. Fig. 2(c) shows the corresponding phase delay due to the simulated evanescent couplers in Fig. 2(b). To achieve the desired phase that we previously calculated, we modify a path length within our unit cell,  $\theta_{ex}$  shown in Fig. 1(a), so that  $\theta_{goal} = \theta_c + 2\theta_{ex}$ , where  $\theta_{goal}$  is the desired phase we synthesized previously and  $\theta_c$  is the additional phase caused by the evanescent coupler.

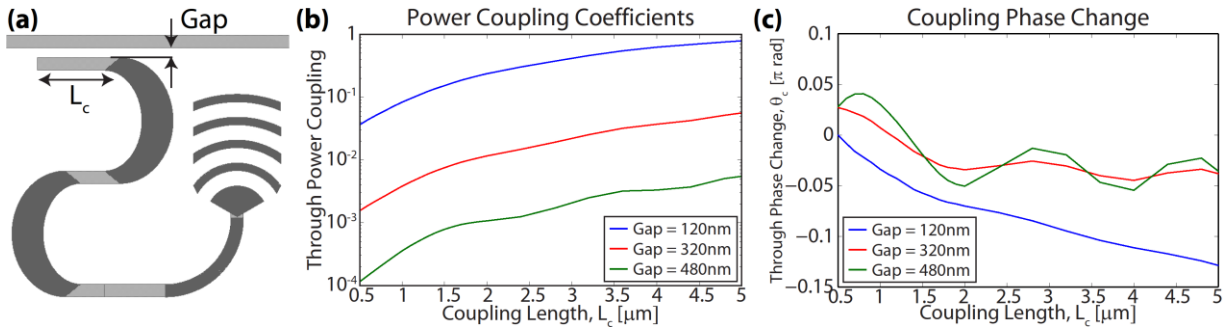


Fig. 2. (a) Gap and coupling length that are being modified in the simulations. (b) Power coupling coefficient change due to varying coupler gap and length. (c) Coupler phase change when varying coupler gap and length.

### 3. Simulation Results

To demonstrate the capability of this design, a phased array that emits the MIT logo separated into 3 output planes with the "M", the "I", and the "T" at 7mm, 14mm, and 28mm, respectively, from the array was simulated. The desired output planes are the individual letters of the MIT logo at the distances given above with uniform phase and intensity distributions. A depiction of the back propagation of these uniform flat phase fronts can be seen in Fig. 3(a). Each plane was back propagated to the phased array and summed. After synthesizing the needed antenna parameters, the result of the initial attempt can be seen in Fig. 3(b). While the individual letters focus in at the desired distance from the array, the effects from the other two letters are still prominent. This effect could be reduced by increasing the distances between the desired planes. However, the distance cannot be increased indefinitely because, as we see in Fig. 3(a), the output planes are not fully captured by the area of the phased array due to the nature of diffraction and

back propagation. As our letters move farther from the phased array, less of the information from the output planes is captured by the phased array, which leads to a degradation of output quality.

One issue is that by simply taking the intensity distributions of desired output images and back propagating them, the array is attempting to produce output planes with uniform phase. This leads to collimated light, which will not disperse greatly with changes in distance. This is evident in the fact that the rough shapes of the non-focused letters are still visible in the planes they shouldn't exist in. To eliminate this effect, small random phase can be added to the desired output images prior to the back propagation. This reduces the issues with the collimated light as the letters will now have non-uniform phases to avoid having all of the pixels constructively interfere straight up and down. Utilizing de-collimated light will allow the letters to disperse faster with distance.

Another issue arises from the back propagation itself. As mentioned earlier, the back propagation of the output is not focused on the area of the phased array, but rather spread out due to the nature of diffraction or defocusing mentioned above. Information is then lost unless we expand the size of the array. This can be fixed by adding a circular phase front with radius equal to the propagation distance prior to back propagation as seen in Fig. 3(c). This allows more of the desired output planes to be captured in a smaller phased array area when it is back propagated. The order of the random phase added earlier is smaller than this circular phase front so that our solution to the back propagation issue is not disturbed. The output with the random circular phase front in the desired planes can be seen in Fig. 3(d). The effects from other planes is much smaller than the letter in focus in comparison to the initial attempt. The output amplitude distribution of each letter appears less uniform than before because of the random phase addition.

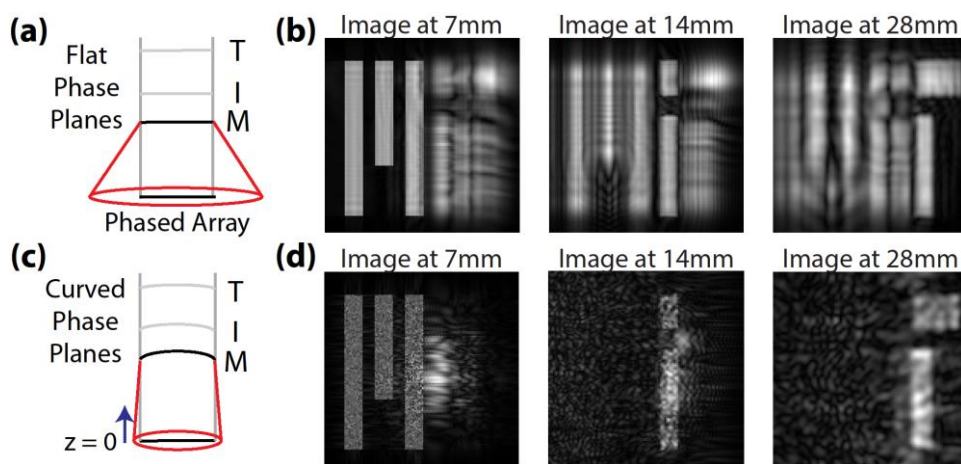


Fig. 3. (a) Back propagated uniform flat phase front field. (b) Output of the phased array emitting “MIT” using back propagation of the flat phase front. (c) Addition of circular phase front to back propagate more accurately to the phased array area. (d) Improved output due to the addition of random and circular phase fronts prior to back propagation.

#### 4. Conclusion

In conclusion, we introduce a method to generate the amplitude and phase distributions required to design an optical phased array that emits arbitrary 3D holograms in the near field by utilizing Fresnel back propagation. We have shown that these parameters can be realizable with a 128x128 antenna phased array with an area of 1.2x1.2mm. Simulations of simple implementations show the desired focusing at varying planes, but effects from other planes are present. Improvements to the quality of the output images can be achieved by including a small random phase distribution on desired output image planes to de-collimate the beams and adding a circular phase front to each desired plane to improve the accuracy of the back propagation without increasing the size of the array.

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