Generating light waves in 3D using communication modes

Vinicius S. de Angelis,[1,2] Ahmed H. Dorrah,[1] Leonardo A. Ambrosio,[1] David A. B. Miller,[3] and Federico Capasso[1,*]

[1] *Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA*
[2] *Department of Electrical and Computer Engineering, São Carlos School of Engineering, University of Sao Paulo, Sao Carlos, SP, Brazil*
[3] *Ginzton Laboratory, Stanford University, Stanford, CA, USA*

[*] *capasso@seas.harvard.edu*

Abstract: We demonstrate a new wavefront shaping method based on interfering the orthogonal communication modes, computed from the singular value decomposition. The light waves exhibit high resolution and minimal cross-talk, and can find applications in holography and light-matter interactions.

Introduction: The ability to precisely control light intensity in 3D volumes is highly in demand in many applications in optics. In the literature, current techniques have to rely on optimization algorithms to enhance the quality of the reconstruction of the target scenes, which in turn add computational cost. In particular, multiplane projection methods must apply these algorithms to minimize interference between the transverse planes that form a scene [1]. Similarly, light sheet holography [2], which constructs a target scene by assembling a set of non-diffracting light threads all oriented parallel to the propagation direction and with their intensity modulated by a superposition of Bessel beams, is limited by the transverse cross-talk between the light threads and an optimization algorithm must be applied to enhance the transverse resolution of the projected scenes [3]. In this work, we propose and demonstrate a new wavefront shaping method that synthesizes a target 3D scene by interfering the optimal waves that can be hosted in a given receiving space using singular value decomposition (SVD) modal optics [4,5].

Concept: We first distribute a collection of receiving points in a 3D domain over which a target scene is to be projected. Spaced by a finite longitudinal distance L, we also define a transverse plane as a source space, composed of a collection of source points (a $p_x \times p_y$ array). A distribution example is shown in Fig. 1(a) in which the receiving space consists of a set of uniformly spaced horizontal planes. Establishing a coupling operator G_{SR} between the source and receiving spaces, we perform the SVD of G_{SR} to compute its communication modes, a set of orthogonal source functions $|\Psi_S\rangle$ that couple one by one to a set of receiving waves $|\Phi_R\rangle$, i.e., $G_{SR}|\Psi_{S,j}\rangle = s_j|\Phi_{R,j}\rangle$, in which s_j are the singular values of G_{SR} [4]. For free space, G_{SR} can be described by a Green's function $G_{SR,\lambda}(\mathbf{r}_R, \mathbf{r}_S, t) = -\exp(i|\mathbf{r}_R - \mathbf{r}_S|2\pi/\lambda)/(4\pi|\mathbf{r}_R - \mathbf{r}_S|)$ in which λ is the operating wavelength, and $\mathbf{r}_S$ and $\mathbf{r}_R$ are the position vectors in those spaces. To synthesize a particular target wave Φ_T in the receiving space, we decompose it into the basis of the receiving space and the required source function to generate it is thus given by $\Psi_T = \sum_j (\langle\Phi_{R,j}|\Phi_T\rangle / s_j)|\Psi_{S,j}\rangle$ [5].

Experimental setup: We optically reconstruct the resulting wave from the required source function at $\lambda = 532$ nm using a standard digital holography system comprising a spatial light modulator (reflective phase-only with 8μm pixel pitch) as depicted in Fig. 1(b). Using a phase retrieval algorithm, the resulting wave is encoded in the first diffraction order, filtered in the Fourier plane of the $4f$ lens system and recovered in the front focal plane of the second lens. A CCD camera mounted on a z-translation stage is used to measure the resulting wave.

Results: Examples of light waves computed using communication modes are shown in Fig. 1(c) for a single horizontal receiving plane and in Fig. 1(d) for a set of ten equally spaced horizontal receiving planes. The number of points and spacing distances adopted for the source and receiving spaces in each case are listed in Table 1.

Table 1. Number of source and receiving points and spacing distances for each example in Fig. 1.

Fig.	$p_x \times p_y$	$p_{x,r} \times p_{y,r} \times p_{z,r}$	d_x, d_y	$d_{x,r}$	$d_{y,r}$	$d_{z,r}$	L
(c)	111 x 222	101 x 1 x 101	λ	λ	-	λ	110λ
(d)	111 x 301	51 x 10 x 51	0.5λ	λ	15λ	λ	50λ

The results show 2D and 3D structured light waves with high fidelity, contrast, intensity uniformity, and resolution. Additionally in Fig. 1(d) the 3D light wave exhibits a high level of depth perception with minimal level of cross-talk between the reconstructed intensity profiles of the eight projected digits.

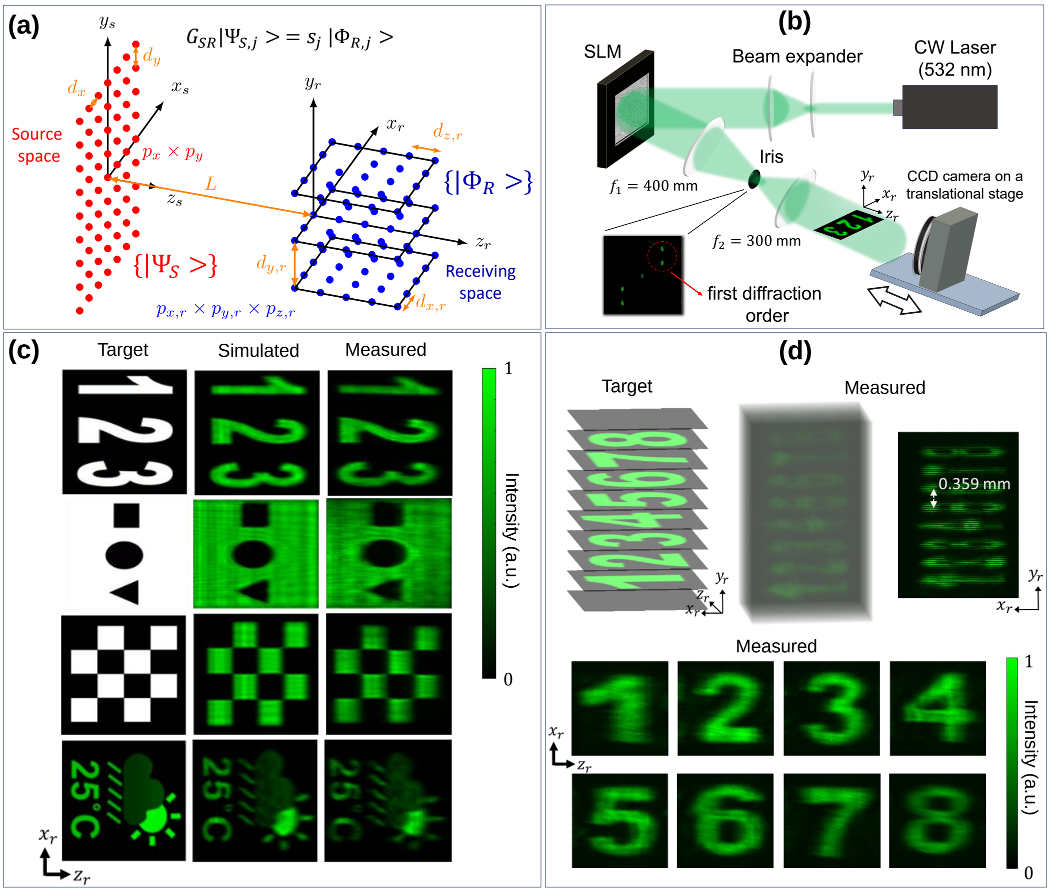

Fig. 1. (a) For a transverse source plane and a set of horizontal receiving planes we compute the associated communication modes (orthogonal source and receiving functions, $|\Psi_S\rangle$ and $|\Phi_R\rangle$) by performing the singular value decomposition of a coupling operator G_{SR} connecting these spaces. A target wave is synthesized by decomposing it into the receiving basis. Its required source function is computed in the source basis. (b) The optical reconstruction of the resulting wave from the source function is done using a standard digital holography system comprising a reflective phase-only spatial light modulator. The resulting wave is encoded in the first diffraction order, filtered in the Fourier plane of the $4f$ lens system and recovered in the front focal plane of the second lens. Transverse planes of the resulting wave are recorded by a CCD camera mounted on a translational stage. (c) Examples of 2D structured light waves and (d) of a 3D pattern volume of light.

Conclusion: We demonstrated a new wavefront shaping method based on interfering the optimum communication modes connecting a source plane and a set of receiving horizontal planes. We envision this method to be beneficial in areas that require controlling light's intensity with high precision, notably in materials processing, light-matter interaction and volumetric displays. Our method can also be favorable in real-time applications. Once the communication modes are computed for a specific source and receiving configuration, we only need to update the complex weights of these modes to construct distinct patterns of light. This process can be implemented and parallelized using GPUs.

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