



(51) International Patent Classification:

G02F 1/01 (2006.01) G02B 5/18 (2006.01)
G06N 3/067 (2006.01) G02B 26/05 (2006.01)

(21) International Application Number:

PCT/US2024/054791

(22) International Filing Date:

06 November 2024 (06.11.2024)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

63/596,940 07 November 2023 (07.11.2023) US

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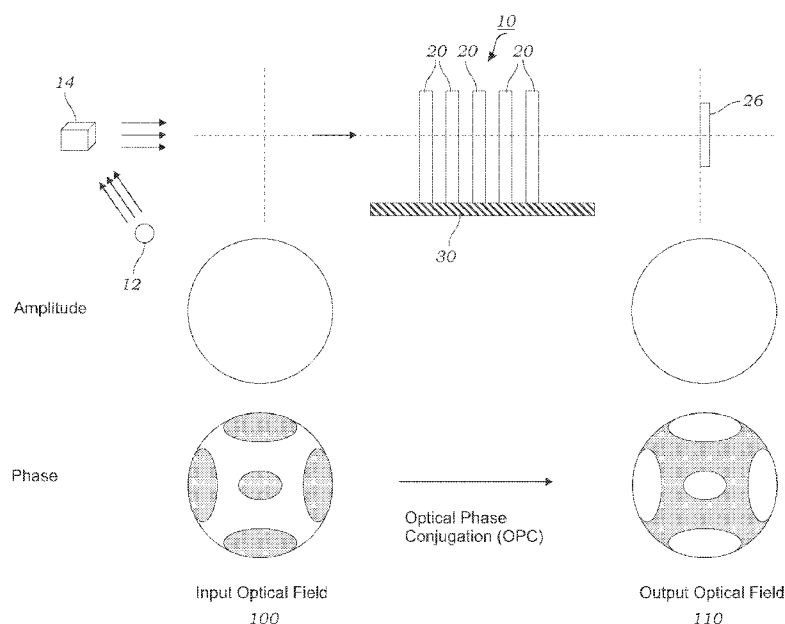
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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA,

(54) Title: ALL-OPTICAL PHASE CONJUGATION USING DIFFRACTIVE WAVEFRONT PROCESSING

FIG. 1A



(57) **Abstract:** A diffractive wavefront processor approximates the all-optical phase conjugation (OPC) operation for input fields with phase aberrations. A set of passive diffractive layers was optimized to all-optically process an arbitrary phase-aberrated input field, producing an output field with a phase distribution that is the conjugate of the input wave. Operation of the wavefront processor was experimentally validated by using fabricated diffractive layers trained using deep learning and performing OPC on phase distortions never seen during training. The diffractive wavefront processor successfully performed the OPC task through a shallow volume that axially spans tens of wavelengths. A diffractive phase-conjugate mirror was also created by combining deep learning-optimized diffractive layers with a standard mirror. The diffractive wavefront processor can be used for diverse OPC-related applications, e.g., turbidity suppression and aberration correction, and is also adaptable to different spectral bands of the electromagnetic spectrum.

NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO,
RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH,
TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS,
ZA, ZM, ZW.

- (84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

ALL-OPTICAL PHASE CONJUGATION USING DIFFRACTIVE WAVEFRONT PROCESSING

Related Application

[0001] This Application claims priority to U.S. Provisional Patent Application No. 63/596,940 filed on November 7, 2023, which is hereby incorporated by reference. Priority is claimed pursuant to 35 U.S.C. § 119 and any other applicable statute.

Technical Field

[0002] The technical field generally relates to devices and methods for performing optical phase conjugation (OPC) using all-optical processing. More specifically, the technical field relates to a diffractive wavefront processor that approximates all-optical phase conjugation operations for input fields with phase aberrations.

Statement Regarding Federally Sponsored

Research and Development

[0003] This invention was made with government support under DE-SC0023088 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

Background

[0004] Optical phase conjugation (OPC) has been used to counteract wavefront distortions by synthesizing a wave that is the complex conjugate of an impinging distorted wave, which can retrace the original propagation path and thereby “undo” the effects of wavefront-induced distortions. Over half a century ago, a seminal work unveiled that OPC could counteract optical scattering using a photorefractive crystal as the phase-conjugate mirror. Phase conjugation has also been demonstrated by degenerate four-wave mixing in absorbing materials. This unique technique later fostered myriad applications including, but not limited to, laser beam focusing through scattering media, imaging through turbid materials, and improving the performance of optical communication systems, among others. As one implementation of OPC, analog optical phase conjugation (AOPC) harnesses nonlinear materials such as photorefractive materials to store the scattered field and produce its phase conjugate, presenting the merits of rapid and continuous phase modulation. Nevertheless, the predominant drawback of AOPC stems from its low conjugation reflectivity, leading to relatively weak energy in the time-reversed beam. As an alternative, digital optical phase

conjugation (DOPC) methods offer a different approach that uses a digital camera in an interferometric set-up to capture the optical wavefront information and digitally produce an OPC field, which can provide much higher conjugation reflectivity. However, DOPC is challenged with its intrinsically slower response, which results in playback latencies of tens of milliseconds and discrete modulation units on the order of several micrometers. In addition, the requirement of high-sensitivity interferometric/holographic imaging set-ups and light field modulation components such as spatial light modulators (SLMs) also bring considerable cost, system complexity and large footprint to existing DOPC solutions. Moreover, the digital recovery and processing of the optical phase information also add to the computational load of these DOPC systems.

[0005] Deep learning-based engineering of materials has recently emerged as a new approach for the inverse design of optical systems for various non-intuitive and nontrivial functions. By leveraging multiple cascaded diffractive layers that are spatially engineered with wavelength-scale features, optimized using deep learning, a diffractive optical network (or a diffractive deep neural network, D²NN) can be formed to perform universal linear transformations through the modulation of optical fields, and has been demonstrated for various applications including multispectral imaging, quantitative phase imaging, unidirectional imaging, pulse shaping, spectral filtering, etc. The unique advantage of this diffraction-based visual computing platform lies in its ability to allow the thin diffractive material to directly interact with the input field wavefront and process the light field *in situ*, thereby significantly reducing or even eliminating the need for digital post-processing. Also, the processing is performed all-optically, using passive materials that do not consume power.

Summary

[0006] Here, an all-optical phase conjugation framework is disclosed that is based on deep learning-engineered diffractive optical structures, which collectively perform phase conjugation on optical fields with unknown phase aberrations. The OPC task is completed at the speed of light propagation through a thin diffractive volume that axially spans $\sim 84\lambda$, where λ denotes the operating wavelength of the system. A diffractive wavefront processor is disclosed that uses, in one embodiment, multiple successively positioned dielectric diffractive layers, where each layer is spatially coded with hundreds of thousands of diffractive features, each engineered at a half-wavelength lateral pitch. Once optimized through deep learning in a computer, these diffractive layers are 3D fabricated to form a physical embodiment of the

wavefront processor capable of processing a phase-distorted input wavefront that passes through its input aperture. This diffractive all-optical processing results in a phase profile at the output aperture, representing a conjugated version of the input phase distribution. Due to the use of passive optical modulation components in this diffractive wavefront processor, the OPC operation is solely driven by the intrinsic power of the input optical field, eliminating the need for any digital processing or other external power sources except for the illumination light. Moreover, since the diffractive OPC system accomplishes its task in an end-to-end manner as the field propagates through a very thin diffractive volume, it obviates the processing speed constraints commonly imposed by digital computation and light field modulation set-ups employed in traditional DOPC solutions, thus enabling ultra-high-speed phase conjugation operations at nanosecond or even picosecond levels, depending on the operation wavelength.

[0007] To demonstrate the efficacy of the platform, a transmissive diffractive OPC processor was designed composed of 8 diffractive layers to perform phase conjugation at a single wavelength within a short axial length of $\sim 84\lambda$. To train this diffractive wavefront processor design, a training dataset was created by randomly generating phase distributions composed of Zernike polynomials as the input field profiles, each paired with its phase-conjugated counterpart as the ground truth (desired profile) of the output phase. After the training, numerical blind testing was conducted using unseen input fields; when the trained diffractive wavefront processor was tested with phase aberrated input fields composed of 2 randomly selected Zernike polynomials, its output fields had a low phase mean absolute error (MAE) of $<1.5\%$. Moreover, when testing using input phase profiles composed of 3 randomly selected Zernike polynomials, representing different types of phase distortions not included in the training inputs, the resulting phase MAE values still remained $<1.5\%$, highlighting the diffractive wavefront processor's adeptness in processing unknown, complicated phase aberrated input wavefronts. Numerical analyses revealed that, for a range of input phase contrast, the diffractive wavefront processor can be regarded as an approximation of the desired OPC function with minimal errors; however, as the input phase contrast and level of phase aberrations escalate, this approximation becomes less accurate. Furthermore, the "time-reversal" effect of this diffractive OPC framework was numerically demonstrated, which was achieved by symmetrically placing the same phase distortion plane before and after the transmissive diffractive OPC design. In blind testing, the diffractive OPC processor successfully showed phase conjugation operation on a plane wave disturbed by an

unknown, random phase perturbation, proving the utility of the diffractive OPC processor. Additionally, the diffractive processor's capability for multi-wavelength OPC operations was demonstrated, showcasing its practicality for applications spanning different spectral bands.

[0008] As an experimental proof-of-concept demonstration, the diffractive OPC framework was verified using diffractive wavefront processor operating at the terahertz (THz) part of the spectrum. Leveraging 3D printing, a 3-layer diffractive OPC processor was fabricated, trained to perform OPC operation on phase aberrated input wavefronts at a wavelength of 0.75 mm. This fabricated diffractive wavefront processor was positioned centrally between two identical unknown phase perturbation planes that were also 3D-printed, and then tested with an input pinhole object to perform all-optical phase conjugation of aberrated spherical wavefronts. Although the diffractive OPC processor never saw the testing phase aberrations during its training, the experiments culminated in the successful reconstructions of sharply focused spots at the output, mirroring the original image of the pinhole object, experimentally verifying the success of the all-optical phase conjugation operation. Beyond this single-wavelength diffractive OPC design, a diffractive multi-wavelength OPC design was trained and fabricated and its successful operation was demonstrated at three distinct wavelengths (0.75 mm, 0.775 mm and 0.8 mm), experimentally validating the feasibility of the broadband OPC framework in generating multi-wavelength phase-conjugated fields.

[0009] Delving deeper, the diffractive OPC processor was combined with a reflective mirror to form a diffractive phase conjugate mirror. By placing a flat mirror behind the diffractive wavefront processor volume, the output wavefront from the diffractive wavefront processor folds back into the same diffractive layers (i.e., a double-pass configuration), ultimately reaching the same aperture used at the input. Numerical results indicate that this diffractive phase conjugate mirror can be successfully trained to perform phase conjugation of unknown, randomly distorted wavefronts, with error levels almost identical to the transmissive OPC configuration.

[0010] The diffractive processor all-optically performs phase conjugation operation on input optical fields. The presented diffractive OPC platform holds design flexibility since it can function at different parts of the electromagnetic spectrum without retraining or optimizing its diffractive layers by simply scaling its features in proportion to the illumination wavelength. This feature makes the diffractive OPC framework highly desirable for correcting wavefront distortions at various parts of the spectrum where cost-effective and

easy-to-implement phase conjugation solutions do not readily exist, such as the IR and THz bands. Moreover, since isotropic dielectric materials are used to fabricate these diffractive layers, the OPC function is independent of the polarization state of the incident light, which remains unchanged at the output of the diffractive OPC system. Combining these unique advantages, the diffractive OPC framework holds promise for various applications, including e.g., turbidity suppression and phase aberration correction, and can unlock different opportunities across diverse areas, including but not limited to biomedical imaging, microscopy, telescope systems and optical communication.

[0011] In one embodiment, a diffractive wavefront processor for performing optical phase conjugation (OPC) on an input optical field includes one or more optically transmissive and/or reflective layers arranged in an optical path, each of the one or more optically transmissive and/or reflective substrate layers comprising a plurality of physical features formed on or within the one or more optically transmissive or reflective substrate layers and having different transmission and/or reflection properties as a function of the lateral coordinates across each layer, wherein the one or more optically transmissive and/or reflective substrate layers modulate the input optical field to generate an output optical field with a phase distribution that is the conjugate of the input optical field. The one or more optically transmissive and/or reflective substrate layers are designed during a training process with a plurality of input phase distributions and their corresponding conjugated versions to optimize the plurality of physical features formed on or within the one or more optically transmissive or reflective substrate layers to perform OPC on the input optical field.

[0012] In another embodiment, a method of performing optical phase conjugation (OPC) on an input optical field includes providing a diffractive wavefront processor comprising one or more optically transmissive and/or reflective layers arranged in an optical path, each of the one or more optically transmissive and/or reflective substrate layers comprising a plurality of physical features formed on or within the one or more optically transmissive or reflective substrate layers and having different transmission and/or reflection properties as a function of the lateral coordinates across each layer, wherein the one or more optically transmissive and/or reflective substrate layers modulate the input optical field to generate an output optical field with a phase distribution that is the conjugate of the input optical field; and inputting the input optical field to the diffractive wavefront processor and generating the output optical field with a phase distribution that is the conjugate of the input optical field.

Brief Description of the Drawings

[0013] FIG. 1A schematically illustrates a diffractive wavefront processor according to one embodiment. A source of illumination illuminates and object or sample and an input optical field is input to the diffractive wavefront processor. The diffractive wavefront processor then outputs an output optical field where the phase is the conjugate of the input optical field. In this embodiment, the diffractive wavefront processor operates in transmission mode.

[0014] FIG. 1B schematically illustrates a diffractive wavefront processor according to one embodiment. A source of illumination illuminates and object or sample and an input optical field is input to the diffractive wavefront processor. The diffractive wavefront processor then outputs an output optical field where the phase is the conjugate of the input optical field. In this embodiment, the diffractive wavefront processor operates in reflection mode.

[0015] FIG. 2 illustrates a single substrate layer of an optical neural network. The substrate layer may be made from a material that is optically transmissive (for transmission mode) or an optically reflective material (for reflective mode). The substrate layer, which may be formed as a substrate or plate in some embodiments, has surface features formed across the substrate layer. The surface features form a patterned surface (e.g., an array) having different valued transmission (or reflection) coefficients as a function of lateral coordinates across each substrate layer. These surface features act as artificial “neurons” that connect to other “neurons” of other substrate layers of the optical neural network through optical diffraction (or reflection) and alter the phase and/or amplitude of the light wave.

[0016] FIG. 3 schematically illustrates a cross-sectional view of a single substrate layer of an optical neural network according to one embodiment. In this embodiment, the surface features are formed by adjusting the thickness of the substrate layer that forms the optical neural network. These different thicknesses may define peaks and valleys in the substrate layer that act as the artificial “neurons.”

[0017] FIG. 4 schematically illustrates a cross-sectional view of a single substrate layer of an optical neural network according to another embodiment. In this embodiment, the different surface features are formed by altering the material composition or material properties of the single substrate layer at different lateral locations across the substrate layer. This may be accomplished by doping the substrate layer with a dopant or incorporating other optical

materials into the substrate layer. Metamaterials or plasmonic structures may also be incorporated into the substrate layer.

[0018] FIG. 5 schematically illustrates a cross-sectional view of a single substrate layer of an optical neural network according to another embodiment. In this embodiment, the substrate layer is reconfigurable in that the optical properties of the various artificial neurons may be changed, for example, by application of a stimulus (e.g., electrical current or field). An example includes spatial light modulators (SLMs) which can change their optical properties. In this embodiment, the neuronal structure is not fixed and can be dynamically changed or tuned as appropriate. This embodiment, for example, can provide a learning diffractive network or a changeable diffractive network that can be altered on-the-fly (e.g., over time) to improve the performance, compensate for aberrations, or even change another task.

[0019] FIGS. 6A-6B illustrate the schematic and operation mechanism of a transmissive diffractive optical phase conjugation (OPC) processor. FIG. 6A is an optical layout of a diffractive OPC processor that operates in transmission geometry. This OPC processor is composed of K passive diffractive layers ($L_1 - L_K$), jointly trained using deep learning to perform OPC of an incoming complex field $i = e^{j\psi}$ with unknown phase aberrations ψ . FIG. 6B is a pipeline of the demonstrated diffractive OPC framework. The resulting output complex field o within the output aperture represents the phase-conjugated version of the input field, i.e., $o \approx \alpha \cdot o^{(\text{GT})} = \alpha \cdot i^* = \alpha \cdot e^{-j\psi}$.

[0020] FIGS. 7A-7E illustrate the transmissive diffractive OPC processor design (FIG. 7A) and the visualization of the diffractive output field examples. FIG. 7A is an illustration of a transmissive diffractive OPC processor. FIG. 7B shows the thickness profiles of the resulting diffractive layers trained through deep learning. FIG. 7C illustrates the amplitude and phase profiles of the exemplary output complex fields produced by the diffractive OPC processor subject to phase aberrated input fields. These input fields possess phase profiles constituted by two random Zernike polynomial terms, never seen during the training stage. For each of these diffractive output fields, its ground truth with perfect phase conjugation is also shown, along with the error map visualizing the absolute amplitude and phase differences between the output field and the ground truth. FIG. 7D shows the same as FIG. 7C, but the used input fields are constituted by only one random Zernike polynomial term, never seen during the training stage. FIG. 7E shows the same as FIG. 7C and FIG. 7D, but

the used input fields are constituted by three random Zernike polynomial terms, never seen during the training stage.

[0021] FIGS. 8A-8B show the impact of the phase contrast of aberrated input fields on the performance of the OPC processor using the diffractive wavefront processor design shown in FIG. 6B. FIG. 8A illustrates the amplitude and phase MAE values between the diffractive OPC outputs and their ground truth as a function of the input phase contrast parameter α_{test} . Metrics are benchmarked across the dataset, reported as mean values with SDs shown as error bars. This quantification is performed utilizing the same testing set as in FIG. 6D. α_{test} indicates that the input complex field has a dynamic phase range of $[0, \alpha_{\text{test}}\pi]$. FIG. 8B shows exemplary visualization of the output complex fields all-optically synthesized by the diffractive OPC processor when using phase aberrated input fields with different phase contrast α_{test} , along with their ground truth and absolute error maps.

[0022] FIGS. 9A-9C show simulation results for correcting phase aberration-induced wavefront distortions using the diffractive OPC design shown in FIG. 6B. FIG. 9A is an illustration of a scenario that leverages the diffractive OPC processor to correct phase aberration-induced wavefront perturbations. The random, unknown phase perturbations induced before and after the diffractive wavefront processor are identical to each other. FIG. 9B shows examples of the output complex fields immediately after the second phase perturbation plane. FIG. 9C illustrates intensity distributions obtained by focusing the output fields in (FIG. 9B) through a diffraction-limited lens.

[0023] FIGS. 10A-10D illustrate different views of the experimental set-up of the transmissive diffractive OPC processor. FIG. 10A is a schematic illustration of a diffractive OPC processor composed of three diffractive layers (L_1, L_2, L_3) to perform OPC operation on a diverging wavefront, emitted by a pinhole-like object and subsequently distorted by a random, unknown phase perturbation plane (P) – which was never seen during the training process. The second phase perturbation plane (P) positioned after the diffractive OPC processor is identical to the first one to test the efficacy of the phase conjugation operation. FIG. 10B shows the thickness profiles of the trained (modeled) diffractive layers (left column) and the photographs of their fabricated versions using 3D printing (right column). FIG. 10C is a schematic of the terahertz imaging set-up. FIG. 10D shows photographic images of the experimental set-up, including the fabricated diffractive OPC processor (inset).

[0024] FIGS. 11A-11B illustrate experimental results of the transmissive diffractive OPC design shown in FIG. 10B. FIG. 11A is a visualization of the phase perturbation planes, along

with the photographs of their fabricated versions. FIG. 11B shows the numerically simulated and experimentally measured intensity distributions at the output plane, compared with the free-space output results in the absence of the diffractive OPC processor.

[0025] FIGS. 12A-12B illustrates the impact of the number of diffractive layers on the phase conjugation performance and the output diffraction efficiency of the diffractive OPC processors. FIG. 12A shows phase MAE values and the output diffraction efficiencies of the diffractive OPC outputs as a function of the number of layers (K) used in the diffractive OPC processor design. Metrics are benchmarked across the dataset, reported as mean values with SDs shown as error bars. FIG. 12B shows exemplary visualization of the diffractive output fields produced by various diffractive OPC processor designs with different K values (4 to 10).

[0026] FIGS. 13A-13B illustrate the tradeoff between the all-optical phase conjugation performance and the output diffraction efficiency of the diffractive OPC processors. FIG. 13A shows the phase MAE values (left) and the amplitude MAE values (right) of the diffractive OPC design output fields with various levels of diffraction efficiency penalty, plotted as a function of the output diffraction efficiencies. Two sets of diffractive OPC designs using $K = 4$ and 8 diffractive layers were trained and blindly tested. Specifically, ① and ② depict different 4-layer diffractive designs resulting from the use of $\beta_{\text{Eff}} = 0$ and $\beta_{\text{Eff}} = 1$, respectively, which refer to the weight of the diffraction efficiency-related penalty in the training loss function (see Eq. (18)). ③ and ④ represent the counterparts of ① and ② for the designs with $K = 8$ diffractive layers. FIG. 13B shows exemplary visualization of the diffractive output fields produced by various diffractive OPC processor designs with different K values (4 and 8) and various levels of diffraction efficiency-related penalty term.

[0027] FIGS. 14A-14E illustrate the diffractive phase-conjugate mirror design (FIGS. 14A, 14B) and the visualization of the output field examples (14C-14E). FIG. 14A illustrates a diffractive OPC processor operating in reflection mode, together with a standard mirror, forming a diffractive phase-conjugate mirror. FIG. 14B is a comparison of the phase error values and the amplitude error values between reflective OPC designs and transmissive OPC designs using different amplitude MSE thresholds (V) during their training/design. Metrics are benchmarked across the dataset, reported as mean values with SDs shown as error bars. FIGS. 14C, 14D, and 14E are the same as FIGS. 7C, 7D, 7E, except for using the diffractive phase-conjugate mirror design.

[0028] FIGS. 15A-15B illustrate schematic of alternative designs. FIG. 15A illustrates a similar schematic illustration as FIG. 10A with four alternative designs are considered here: (1) a three-layer diffractive OPC processor, (2) a single-layer diffractive OPC processor, (3) a thin lens, and (4) free space. FIG. 15B shows phase profiles of the trained diffractive layers of the three-layer and one-layer diffractive OPC processor designs, as well as a conventional thin lens (perfect lens).

[0029] FIG. 16 illustrates simulation results for beam focusing through random phase perturbations. The simulated field amplitude distributions at the output plane are shown using the different designs illustrated in FIGS. 15A-15B.

[0030] FIGS. 17A and 17B illustrate the schematic and operation mechanism of a transmissive diffractive multi-wavelength OPC processor. FIG. 17A illustrates a performing phase conjugation for N_w distinct wavelengths simultaneously. FIG. 17B illustrates the thickness profiles of the resulting diffractive layers for the diffractive multi-wavelength OPC processor trained for $N_w = 8$.

[0031] FIG. 18 illustrates the spectral multiplexing capacity and the scalability analysis of diffractive multi-wavelength OPC processors. Phase error values as a function of the number of wavelengths, N_w . Bars represent different numbers of trainable features in the diffractive OPC processor. Metrics are benchmarked across the dataset, reported as mean values with SDs shown as error bars.

[0032] FIGS. 19A-19B illustrates the visualization of the multi-wavelength OPC processor output fields using a broadband diffractive processor operating at the visible band. FIG. 19A illustrates amplitude and phase profiles of exemplary multi-wavelength output complex fields synthesized by the diffractive OPC processor fed with phase aberrated input fields; in this case, each wavelength channel has an independent aberration profile, constituted by two random Zernike polynomial terms, never seen during the training stage. For each of these diffractive output fields, its ground truth with perfect phase conjugation is also shown, along with the error map visualizing the absolute amplitude and phase differences between the output field and the ground truth. FIG. 19B is the same as FIG. 19A, except for demonstrating the external generalization capability using three random Zernike polynomials; in this case, each wavelength channel has an independent aberration profile, constituted by three random Zernike polynomial terms, never seen during the training stage. Here, the diffractive multi-wavelength OPC processor performs independent phase

conjugation at eight distinct wavelengths $\{\lambda_1, \lambda_2, \dots, \lambda_8\}$, ranging from 400 nm to 750 nm with 50 nm increments.

[0033] FIGS. 20A and 20B illustrate the visualization of the multi-wavelength OPC output fields using a broadband diffractive processor employing a dispersion-free material. Same as FIGS. 19A, 19B, except a dispersion-free material was used for the diffractive layers (FIG. 20A= two random Zernike polynomial terms; FIG. 20B= three random Zernike polynomials). Here, the diffractive multi-wavelength OPC processor performs independent phase conjugation at eight distinct wavelengths $\{\lambda_1, \lambda_2, \dots, \lambda_8\}$, ranging from 400 nm to 750 nm with 50 nm increments.

[0034] FIGS. 21A and 21B illustrate experimental results of the transmissive diffractive multi-wavelength OPC processor design. FIG. 21A shows the thickness profiles of the trained diffractive layers (left) and the photographs of their fabricated versions using 3D printing (right). FIG. 21B illustrates phase perturbation planes (P) used in the experiments, along with their resulting output multi-wavelength intensity distributions obtained from numerical simulations and experimental measurements.

[0035] FIG. 22 illustrates phase profiles of the resulting layers for the diffractive phase-conjugate mirror design.

[0036] FIGS. 23A and 23B illustrate output visualization of the comparison between the transmissive OPC processor designs and the reflective OPC processor designs using different amplitude MSE thresholds (V) employed during the training stage. FIG. 23A shows diffractive output examples of the reflective OPC processor designs and the transmissive OPC processor designs trained with $V = 0.02$. FIG. 23B is the same as FIG. 23A., except for $V=0.005$.

[0037] FIGS. 24A-24D illustrate the results for testing the external generalization performance of the diffractive OPC processor design. FIG. 24A illustrates phase error values of the diffractive OPC processor outputs as a function of the number of Zernike polynomials. The shaded transparent area indicates the range of the standard deviations. FIG. 24B is the same as FIG. 7C. FIG. 24C is the same as FIG. 24B, but the aberrated input fields are constituted by five randomly selected Zernike polynomial terms, never seen during the training stage. FIG. 24D is the same as FIG. 24B, but the aberrated input fields are constituted by eight randomly selected Zernike polynomial terms, never seen during the training stage.

[0038] FIGS. 25A and 25B illustrate the impact of lateral misalignments on the phase conjugation performance of the vaccinated diffractive OPC processors. FIG. 25A illustrates the phase error values of the diffractive OPC processor outputs as a function of random lateral shifts. FIG. 25B shows the amplitude error as a function of random lateral shifts. In both plots, transparent areas indicate the range of the standard deviations. The zero lateral shift curves (0λ) represent the performance of the diffractive OPC processor previously shown in FIG. 7A; the other curves represent the vaccinated diffractive OPC processor designs. Specifically, when the diffractive OPC processors were trained with random lateral displacements of the diffractive layers, the corresponding blind testing phase error maintained a low level of $<4\%$ when the random misalignment used in the testing phase did not exceed the maximum misalignment magnitude used in the training phase.

[0039] FIGS. 26A and 26B illustrate the impact of axial misalignments on the phase conjugation performance of vaccinated diffractive OPC processors. FIG. 26A shows the phase error values of the diffractive OPC processor outputs as a function of random axial shifts. FIG. 26B shows the amplitude error values of the diffractive OPC processor outputs as a function of random axial shifts. In both plots, transparent areas indicate the ranges of the standard deviations.

[0040] FIGS. 27A and 27B illustrate the output visualization of vaccinated diffractive OPC processors with different degrees of lateral misalignments. Examples of the diffractive OPC processor output fields with different degrees of vaccination. FIG. 27A shows the illustrate aberrated input fields are generated by the combination of two randomly selected Zernike polynomials. FIG. 27B is the FIG. 27A, except that five randomly selected Zernike polynomials were used.

[0041] FIGS. 28A and 28B illustrate the output visualization of vaccinated diffractive OPC processors with different degrees of axial misalignments. Examples of the diffractive OPC processor output fields with different degrees of vaccination. FIG. 28A illustrates the aberrated input fields are generated by the combination of two randomly selected Zernike polynomials. FIG. 28B is the same as FIG. 27A, except that five randomly selected Zernike polynomials were used.

Detailed Description of Illustrated Embodiments

[0042] With reference to FIG. 1A the diffractive wavefront processor 10 contains one or more diffractive layers 20 that are physical layers which may be formed as a physical

substrate or matrix of optically transmissive material (for transmission mode) or optically reflective material (for reflective mode one). In transmission mode, which is illustrated in FIG. 1A, light or radiation passes through the diffractive layers 20. Conversely, in reflective mode, as seen in FIG. 1B, light or radiation reflects off the substrate layer(s) 20. Exemplary materials that may be used for the diffractive layers 20 include polymers and plastics (e.g., those used in additive manufacturing techniques such as 3D printing) as well as semiconductor-based materials (e.g., silicon and oxides thereof, gallium arsenide and oxides thereof), crystalline materials or amorphous materials such as glass and combinations of the same. Metal coated materials may be used for reflective diffractive layers 20. In one embodiment, the diffractive layers 20 are made from an isotropic dielectric material.

[0043] The diffractive wavefront processor 10, in some embodiments, includes an illumination source 12 that is used to illuminate a sample or objects 14 to be imaged. For example, light from the illumination that reflects off or passes through a sample or object(s) forms an input optical field 100 that is input to the diffractive wavefront processor 10. Alternatively, a natural source of light (e.g., ambient light) may generate the input optical field 100 to the diffractive wavefront processor 10. The input optical field 100 has one or more aberrations or other artifacts that are corrected or mitigated by the diffractive wavefront processor 10. The aberrations may include a phase profile representing coma, astigmatism, spherical aberration, and/or trefoil. In other embodiments, the input optical field 100 has passed through turbid media and the diffractive wavefront processor 10 is used for turbidity suppression. Likewise, the diffractive wavefront processor 10 may be compensate or mitigate atmospheric aberrations. The aberrations may also be caused by the input optical field 100 passing through diffuser(s) or scatterer(s) or diffusive and/or scattering media.

[0044] As seen in FIGS. 1A and 1B, the one or more optically transmissive and/or reflective diffractive layers 20 of the diffractive wavefront processor 10 modulate the input optical field 100 to generate an output optical field 110 with a phase distribution that is the conjugate of the input optical field 100. FIGS. 1A and 1B illustrate how the phase image of the output optical field 110 is the conjugate of the input optical field 100. The amplitude channel is substantially unaffected as seen in FIGS. 1A and 1B. In some embodiments, an image sensor 26 is located along the optical path to capture the output optical field 110. The image sensor 26, however, is optional and in some embodiments, the output optical field 100 may be projected onto a surface or another device (e.g., a lens of another camera or the like). In some embodiments, such as illustrated in FIG. 14A, the output optical field 110 is reflected

off of a mirror M and passes through (or reflected off) the diffractive layers 20 where it is reflected back and appears at an input aperture 32.

[0045] With reference to FIGS. 1A, 1B, 1-5, 6A, 6B, 7B each diffractive layer 20 of the diffractive wavefront processor 10 has a plurality of physical features 22 as seen in FIGS. 2-5 formed on the surface of the diffractive layer 20 or within the diffractive layer 20 itself that collectively define a pattern of physical locations along the length and width of each diffractive layer 20 that have varied transmission properties (or varied reflection properties). The physical features 22 formed on or in the diffractive layers 20 thus create a pattern of physical locations on or within the diffractive layers 20 that have different valued transmission or reflection properties as a function of lateral coordinates (e.g., length and width and in some embodiments depth) across each diffractive layer 20. In some embodiments, each separate physical feature 22 may define a discrete physical location on the diffractive layer 20 while in other embodiments, multiple physical features 22 may combine or collectively define a physical region with a particular transmission (or reflection) property.

[0046] The pattern of physical locations formed by the physical features 22 may define, in some embodiments, an array located across the surface of the diffractive layer 20. With reference to FIGS. 2 and 3, the diffractive layer 20 in one embodiment is a two-dimensional generally planar substrate having a length (L), width (W), and thickness (t) that all may vary depending on the particular application. In other embodiments, the diffractive layer 20 may be non-planar such as, for example, curved. In addition, while FIG. 2 illustrates a rectangular or square-shaped diffractive layer 20 different geometries are contemplated. The physical features 22 and the physical regions formed thereby act as artificial “neurons” that connect to other “neurons” of other diffractive layers 20 of the diffractive wavefront processor 10 through optical diffraction (or reflection) and alter the phase and/or amplitude of the light wave. The particular number and density of the physical features 22 or artificial neurons that are formed in each diffractive layer 20 may vary depending on the type of application. In some embodiments, the total number of artificial neurons may only need to be in the hundreds or thousands while in other embodiments, hundreds of thousands or millions of neurons or more may be used. Likewise, the number of diffractive layers 20 that are used in the diffractive wavefront processor 10 may vary although it typically ranges from at least two diffractive layers 20 to less than ten diffractive layers 20. In some embodiments, only a single diffractive layer 20 will suffice.

[0047] FIGS. 2 and 3 illustrates one embodiment of how different physical features 22 are formed in the diffractive layer 20. In this embodiment, a diffractive layer 20 has different thicknesses (t) of material at different lateral locations along the diffractive layer 20. In one embodiment, the different thicknesses (t) modulate the phase of the light passing through the diffractive layer 20. This type of physical feature 22 may be used, for instance, in the transmission mode embodiment (e.g., FIG. 1A). The different thicknesses of material in the diffractive layer 20 forms a plurality of discrete “peaks” and “valleys” that control the transmission property/coefficient of the neurons formed in the diffractive layer 20. The different thicknesses of the diffractive layer 20 may be formed using additive manufacturing techniques (e.g., 3D printing) or lithographic methods utilized in semiconductor processing. For example, the design of the diffractive layers 20 may be stored in a stereolithographic file format (e.g., .stl file format) which is then used to 3D print the diffractive layers 20. Other manufacturing techniques include well-known wet and dry etching processes that can form very small lithographic features on a diffractive layer 20. Lithographic methods may be used to form very small and dense physical features 22 on the diffractive layer 20 which may be used with shorter wavelengths of the light. As seen in FIG. 3, in this embodiment, the physical features 22 are fixed in permanent state (i.e., the surface profile is established and remains the same once complete).

[0048] FIG. 4 illustrates another embodiment in which the physical features 22 are created or formed within the diffractive layer 20. In this embodiment, the diffractive layer 20 may have a substantially uniform thickness but have different regions of the diffractive layer 20 have different optical properties. For example, the refractive (or reflective) index of the diffractive layers 20 may altered by doping the diffractive layers 20 with a dopant (e.g., ions or the like) to form the regions of neurons in the diffractive layers 20 with controlled transmission properties (or absorption and/or spectral features). In still other embodiments, optical nonlinearity can be incorporated into the diffractive wavefront processor 10 design using various optical non-linear materials (e.g., crystals, polymers, semiconductor materials, doped glasses, polymers, organic materials, semiconductors, graphene, quantum dots, carbon nanotubes, and the like) that are incorporated into the diffractive layer 20. A masking layer or coating that partially transmits or partially blocks light in different lateral locations on the diffractive layer 20 may also be used to form the neurons on the diffractive layers 20.

[0049] Alternatively, the transmission function of the physical features 22 or neurons can also be engineered by using metamaterial or plasmonic structures. Combinations of all these

techniques may also be used. In other embodiments (FIG. 5), non-passive components may be incorporated into the diffractive layers 20 such as spatial light modulators (SLMs). SLMs are devices that impose spatial varying modulation of the phase, amplitude, or polarization of a light. SLMs may include optically addressed SLMs and electrically addressed SLM. Electric SLMs include liquid crystal-based technologies that are switched by using thin-film transistors (for transmission applications) or silicon backplanes (for reflective applications). Another example of an electric SLM includes magneto-optic devices that use pixelated crystals of aluminum garnet switched by an array of magnetic coils using the magneto-optical effect. Additional electronic SLMs include devices that use nanofabricated deformable or moveable mirrors that are electrostatically controlled to selectively deflect light.

[0050] FIG. 5 schematically illustrates a cross-sectional view of a single diffractive layer 20 of a diffractive wavefront processor 10 according to another embodiment. In this embodiment, the diffractive layer 20 is reconfigurable in that the optical properties of the various physical features 22 that form the artificial neurons may be changed, for example, by application of a stimulus (e.g., electrical current or field). An example includes spatial light modulators (SLMs) discussed above which can change their optical properties. In other embodiments, the layers may use the DC electro-optic effect to introduce optical nonlinearity into the diffractive layers 20 of the diffractive wavefront processor 10 and require a DC electric-field for each diffractive layer 20 of the diffractive wavefront processor 10. This electric-field (or electric current) can be externally applied to each diffractive layer 20 of diffractive wavefront processor 10. Alternatively, one can also use poled materials with very strong built-in electric fields as part of the material (e.g., poled crystals or glasses). In this embodiment, the neuronal structure is not fixed and can be dynamically changed or tuned as appropriate (i.e., changed on demand). This embodiment, for example, can provide a learning diffractive wavefront processor 10 or a changeable diffractive wavefront processor 10 that can be altered on-the-fly to improve the performance, compensate for aberrations, or even change another task.

[0051] As explained herein, a computerized model of the diffractive wavefront processor 10 is first digitally trained. Here, the model of the diffractive wavefront processor 10 is trained to perform OPC on an input optical field 100. In one embodiment, the OPC mitigates or compensates for aberrations in the input optical field 100. The training creates the design of the physical features 22 formed in the one or more diffractive layers 20 that receive the

input optical field 100. Next, using the established model and design for the physical embodiment of the diffractive wavefront processor 10, the actual diffractive layers 20 used in the physical embodiment of the diffractive wavefront processor 10 are then manufactured in accordance with the model or design. The design, in some embodiments, may be embodied in a software format (e.g., SolidWorks, AutoCAD, Inventor, or other computer-aided design (CAD) program or lithographic software program) and may then be manufactured into a physical embodiment that includes the plurality of diffractive layers 20 having the tailored physical features 22 formed therein/thereon. The physical diffractive layers 20, once manufactured may optionally be mounted or disposed in a holder 30 or the like (as seen in FIG. 1A) to maintain the appropriate spacing between the diffractive layers 20 and/or the object. The holder 30 may include a number of slots formed therein to hold the individual diffractive layers 20 and/or object in the required sequence and with the required spacing between adjacent diffractive layers 20 (if needed). The physical diffractive layers 20 may also be integrated into a monolithic structure in other embodiments. The diffractive layers 20 may also be incorporated into a waveguide like an optical fiber.

[0052] Although the diffractive wavefront processor 10 reported herein were primarily designed for the terahertz band, the underlying concept and design approaches are also applicable for defect detection in other parts of the electromagnetic spectrum, including mm-wave, infrared, visible, and X-ray. Such diffractive wavefront processors 10 and systems can find diverse applications, such as industrial manufacturing and quality control, biomedical imaging, material inspection, detection/classification of objects, security screening, autonomous vehicles, microscopy, satellite imagery and the like. The non-destructive and non-invasive nature of this technology platform also makes it a valuable tool for sensitive applications, e.g., cultural heritage preservation and biomedical sensing. This framework can deliver transformative advances in various fields, where defect detection and materials diagnosis are of utmost importance.

[0053] Experimental

[0054] Results

[0055] **Design of a transmissive diffractive OPC processor**

[0056] FIGS. 6A-6B illustrates the general concept of a diffractive OPC processor 10 that operates in transmission, i.e., with an input and an output aperture positioned at the different sides of the diffractive wavefront processor. As depicted in FIG. 6A, a diffractive OPC network or processor 10 composed of K successive diffractive layers 20 ($L_1, \dots, L_K$) is

positioned between the input aperture 32 and output aperture 34, with its primary function to perform optical phase conjugation of the aberrated fields within the input aperture 32 and relay the resulting phase-conjugated fields into the output aperture 34. Each of these diffractive layers 20 is coded with the same number of spatially engineered features 22, each with a lateral width of $\sim\lambda/2$ and a trainable thickness that provides a full phase modulation covering 0 to 2π . The input aperture 32, diffractive layers 20 and output aperture 34 are connected to each other through free space. The intended functionality of this diffractive OPC framework is further elaborated on in FIG. 6B. An incident phase aberrated field $\mathbf{i} = e^{j\Psi}$ with a uniform amplitude and an unknown phase profile Ψ (i.e., input optical field 100) passes through the input aperture 32. After being processed by the diffractive OPC processor 10, the resulting complex field (i.e., output optical field 110) is collected by the output aperture 34, represented as $\mathbf{o} = \mathbf{D}^2\mathbf{NN}\{\mathbf{i} = e^{j\Psi}\}$. The objective function of the diffractive OPC processor 10 is to ensure that, for any phase aberrated input field $\mathbf{i} = e^{j\Psi}$, the diffractive output field $\mathbf{o}$ 110 would exhibit a phase profile that closely approximates the phase-conjugated version of the input field 100, i.e., $\mathbf{o} \approx \alpha \cdot \mathbf{o}^{(\text{GT})} = \alpha \cdot \mathbf{i}^* = \alpha \cdot e^{-j\Psi}$, where GT stands for ground truth, and α is a scalar constant that accounts for the output diffraction efficiency of the OPC processor 10.

[0057] It is worth noting that OPC operations were demonstrated with a unit magnification between the input and output apertures 32, 34, axially separated by several tens of wavelengths. This design choice ensures a relatively high diffraction efficiency within the output aperture of the OPC processor 10, and also allows the precise modeling of the free space propagation between adjacent diffractive planes using the angular spectrum method, with a lateral sampling of $\sim\lambda/2$ at the input and the propagated fields. If phase conjugation with magnification or demagnification at the output field is desired, the implementation of a pyramidal architecture for the diffractive OPC processor 10 may be considered. In that case, the free-space propagation can be modeled using a scalable angular spectrum method or the Fresnel diffraction approach to enable different sampling sizes at the input and output fields 100, 110. These approaches can allow for the efficient design and modeling of diffractive OPC processors 10, accommodating a wider range of structural parameters and applications.

[0058] As a proof-of-concept demonstration, numerical simulations were conducted of the diffractive OPC processor within the terahertz part of the spectrum, at a wavelength of $\lambda = 0.75$ mm. Furthermore, phase distributions formed by Zernike radial polynomials were leveraged as the testbed to assess the phase conjugation capability of the diffractive OPC

framework. Zernike radial polynomials are a set of continuous functions orthogonal over a unit circle, which can be used to describe typical wavefront aberrations or deviations from an ideal wavefront in various optical systems. The mathematical representation of a Zernike radial polynomial is given by:

$$[0059] \quad R_n^m(\rho) = \sum_{k=0}^{\frac{n-m}{2}} \frac{(-1)^k (n-k)!}{k! \left(\frac{n+m}{2}-k\right)! \left(\frac{n-m}{2}-k\right)!} \rho^{n-2k} \quad (1).$$

[0060] Here, ρ denotes the normalized radial coordinate, constrained within the range of $[0, 1]$. Both m and n are nonnegative integers, collectively defining a specific mode of the Zernike polynomial. Practically, the polynomials $\{R_n^m\}$ serve as a basis set for characterizing wavefront aberrations, with each R_n^m corresponding to a distinct type of aberration. For this study, randomly generated combinations of these Zernike polynomials were used, i.e., $\sum_l \beta_l R_{n_l}^{m_l}$, to create a variety of phase distributions. These phase distributions were used as the phase profiles of the input fields $t = e^{j\psi}$ within a circular input aperture 32, to be processed by the diffractive OPC framework.

[0061] To make the diffractive phase conjugation framework successful, it is imperative to train the diffractive model to accommodate a wide variety of phase profiles. With this in mind, a set of 200,000 randomly selected Zernike polynomial phase distributions were generated for training proposes. Each of these phase profiles was formulated by randomly selecting two from the first 28 Zernike polynomials and linearly combining them using random weight coefficients, which can be described as:

$$[0062] \quad \psi = \beta_1 R_{n_1}^{m_1} + \beta_2 R_{n_2}^{m_2} \quad (2),$$

[0063] where $\beta_1 \neq 0$ and $\beta_2 \neq 0$ are the weight coefficients of the polynomials adhering to the constraint that $\beta_1 + \beta_2 = \alpha_{tr}\pi$. During the training data generation, the coefficient β_1 for each ψ was randomly chosen from the range $[0.1\alpha_{tr}\pi, 0.9\alpha_{tr}\pi]$. The polynomial mode numbers, (m_1, m_2) and (n_1, n_2) , were also randomly selected within the ranges of $[-6, 6]$ and $[0, 6]$, respectively, ensuring the selection only from the first 28 Zernike polynomials. With this formulation, each ψ possesses a dynamic range of $[0, \alpha_{tr}\pi]$, where α_{tr} denotes a training phase contrast parameter. In order to facilitate the diffractive OPC network's capability to perform all-optical phase conjugation across different input phase contrast values, α_{tr} was randomly chosen between 0.2 and 1, i.e., $\alpha_{tr} \in U[0.2, 1]$. Based on this diverse set of ψ , their conjugated versions were also generated as the training target (ground truth) of the diffractive

OPC processor 10, thus forming a training dataset consisting of 200,000 input/target complex field pairs.

[0064] The model of the diffractive OPC processor 10 was trained with $K = 8$ successive diffractive layers 20 using an operational wavelength of $\lambda = 0.75$ mm, as illustrated in FIG. 7A. During the training process, the thickness profiles of the diffractive layers 20 were iteratively optimized via error-backpropagation and stochastic gradient descent techniques (see the Methods section for details). The necessity for precise control over the output complex field presents a significant challenge in diffractive optical information processing, approximating a nonlinear OPC function that has not been explored yet. To address this challenge, a new optimization process was used to minimize a specially devised loss function, which compares both the normalized amplitude and phase differences between the diffractive output fields $\mathbf{o}$ 110 and their corresponding ground truth $\mathbf{o}^{(GT)}$. More details regarding the training loss function, numerical forward model and structural parameters of the diffractive OPC processor 10 can be found in the Methods section.

[0065] Performance analysis of a transmissive diffractive OPC processor

[0066] After the deep learning-based optimization of the diffractive OPC processor 10, the resulting diffractive layer thickness profiles are visualized in FIG. 7B. To blindly test the performance of the OPC processor 10 with the trained design, a test set was first created containing 10,000 pairs of input/target fields by following the same approach that was used for constructing the training set, except that each input/target phase profile in this test set has a phase contrast of $\alpha_{\text{test}} = 1$. Stated differently, the input fields in this test set can be represented as $\mathbf{l} = e^{j\Psi}$ and $\Psi = \beta_1 \mathbf{R}_{n_1}^{m_1} + \beta_2 \mathbf{R}_{n_2}^{m_2}$, where $\beta_1 + \beta_2 = \pi$, $\beta_1 \neq 0$ and $\beta_2 \neq 0$, indicating that all the input/target fields have a dynamic phase range of $[0, \pi]$. These input optical fields 100 in the test set were also randomly generated to be different from those in the training set, ensuring that they were never seen before by the trained diffractive model.

[0067] Based on these test input optical fields 100, their corresponding output optical fields 110 produced by the diffractive OPC network 10 were obtained through numerical simulations. To evaluate these results, these output complex fields 110 were first normalized with respect to their ground truth, eliminating the effect of their scaling mismatch caused by the output diffraction efficiency. Following that, the MAE values were computed for both the phase and amplitude components of the normalized output fields compared to the phase-conjugated ground truth, which were termed phase and amplitude MAEs, respectively. Based on this evaluation approach, an average phase MAE of $1.38 \pm 0.12\%$ was achieved across the

entire test set. This suggests that the phase profiles of the output optical fields 110 generated by the diffractive OPC network 10 align closely with the target phase conjugated output distribution, manifesting only minimal discrepancies. On the other hand, the average amplitude MAE was quantified as $8.89 \pm 1.91\%$, which also represents a relatively low error level, despite being larger compared to its phase counterpart. FIG. 7C provides examples of diffractive output optical fields 110 alongside their respective ground truth and error maps. These results illustrate that the diffractive output optical fields 110 exhibit phase distributions almost identical to their ground truth. The amplitude of these output fields also presents a good uniformity across the output aperture 34 of the diffractive OPC design.

[0068] In addition to these blind testing results, another test set of phase aberrated input fields was created with their phase profiles constituted by only a single, randomly selected Zernike polynomial term, i.e., $\Psi = R_n^m$. Such phase distributions, which represent a particular case of Eq. (2) with β_1 or $\beta_2 = 0$, can be used to describe distinct types of phase aberrations, including those frequently occurring in the pupil function of imaging systems such as *coma* and *astigmatism*. The diffractive OPC network 10 was blindly tested using 28 of such input optical fields 100 (randomly generated), where each field corresponds to one of the first 28 Zernike polynomial terms - never seen by the diffractive model during the training process. The resulting diffractive output optical fields 110 based on these input optical fields 100 were then quantitatively compared with their phase-conjugated target fields, which yielded phase and amplitude MAE values of $1.71 \pm 0.14\%$ and $13.13 \pm 2.31\%$, respectively, revealing a decent blind testing performance. This success is also confirmed by visualizing some diffractive output optical fields 110, as shown in FIG. 7D, which correspond to R_2^{-2} , R_3^{-1} , R_4^0 and R_3^{-3} , representing coma, astigmatism, spherical aberration and trefoil, respectively. Here, the output optical fields 110 of the diffractive OPC processor 10 present a successful phase conjugation operation performed on these typical phase aberrations, despite some imperfections in their amplitude components in regions with larger phase values, echoing the prior observations in FIG. 7C.

[0069] Next, the diffractive OPC model was blindly tested using input fields with their phase profiles constituted by a combination of 3 randomly selected Zernike polynomials, i.e., $\Psi = \beta_1 R_{n_1}^{m_1} + \beta_2 R_{n_2}^{m_2} + \beta_3 R_{n_3}^{m_3}$ (i.e., $\beta_1 + \beta_2 + \beta_3 = \pi$, where $\beta_1 \neq 0$, $\beta_2 \neq 0$ and $\beta_3 \neq 0$). This test set demonstrates even more complicated phase structures than those seen during the training. Using randomly generated 10,000 input test fields 100, the same diffractive OPC processor 10 design achieved phase and amplitude MAE values of $1.09 \pm 0.06\%$ and $8.39 \pm$

1.32%, respectively, further demonstrating its generalization success, performing all-optical phase-conjugation on various forms of randomly generated phase aberrations. The visualization of exemplary output optical fields 110 is shown in FIG. 7E, underscoring the framework's robust external generalization capability for more complex phase conjugation tasks that were never represented in the training process.

[0070] In the analyses reported so far, the performance evaluation was conducted using phase-aberrated input fields with $\alpha_{\text{test}} = 1$. To delve deeper into the effects of varying α_{test} on the performance of OPC processor 10, the analysis was extended across an array of α_{test} values: [0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 1.99], using the same diffractive OPC model trained with $\alpha_{\text{tr,max}} = 1$. For this analysis, randomly generated input fields were used with phase profiles characterized by a single Zernike polynomial, i.e., $\Psi = R_n^m$, which corresponds to one of the first 28 Zernike polynomial terms, never seen by the diffractive OPC model during its training process. As shown in FIG. 8A, the resulting normalized amplitude and phase MAE values, plotted as a function of α_{test} , reveal a rising error trend as α_{test} increases. Notably, when $\alpha_{\text{test}} < 1$, the diffractive model consistently delivers phase MAE values below 2%, showcasing its adeptness at phase conjugation tasks in this α_{test} range, which falls within the training ($\alpha_{\text{tr,max}} = 1$). For example, for $\alpha_{\text{test}} = 0.2$, the phase MAE value drops to $0.14 \pm 0.03\%$, highlighting the diffractive OPC model's excellent performance for a smaller range of phase aberrations. However, for $\alpha_{\text{test}} > 1$ (which is outside of the training range), error margins widen considerably, with the most pronounced increase observed at $\alpha_{\text{test}} = 1.99$, where the phase MAE value escalates to $6.83 \pm 0.78\%$, a value nearly four times greater than its counterpart at $\alpha_{\text{test}} = 1$, which stands at $1.71 \pm 0.14\%$. These observations are accentuated in FIG. 8B, which depicts the diffractive output fields 110 at $\alpha_{\text{test}} = 0.2, 1.0$ and 1.8 .

[0071] For larger phase aberrations corresponding to out-of-distribution test values with $\alpha_{\text{test}} > 1$, there is a notable decline in the accuracy of the amplitude and phase output profiles of the diffractive OPC processor 10. This phenomenon stems from the fact that the universal linear transformation capability of a diffractive design provides a less accurate approximation for the OPC operation, which increases the output errors for larger phase aberration values corresponding to $\alpha_{\text{test}} > 1$. On the other hand, the diffractive optical field outputs 110 of the OPC processor 10 almost identically mirror the desired phase-conjugated ground truth when the phase contrast is relatively small, e.g., $\alpha_{\text{test}} < 1$.

[0072] Correction of phase aberration-induced wavefront distortions using a diffractive OPC processor

[0073] To shed more light on the capabilities of the diffractive OPC system in performing all-optical phase conjugation, the time-reversal effect of OPC to counteract wavefront distortions caused by random unknown phase aberrations was tested, as depicted in FIG. 9A. In this scenario, two phase perturbation planes that exhibit identical but randomly selected, unknown phase aberrations were positioned, before and after a diffractive OPC processor 10. Upon encountering the first phase aberration plane, an incoming plane wave has its wavefront distorted in an unknown, random manner. Subsequently, after passing through the diffractive OPC processor 10, the field of the outgoing wave is conjugated, which then impinges on the second phase aberration plane. Ideally, for a perfect OPC device, the phase-conjugated wavefront, after passing through the second phase aberration plane, should manifest as a uniform plane wave – cleaned from any aberrations. To validate/test this behavior of the diffractive OPC design, coma, astigmatism, spherical aberration and trefoil were selected as different forms of random phase aberrations and employed the same diffractive OPC design shown in FIG. 7B, without any additional optimization. The results of this analysis are presented in FIG. 9B, which revealed a decent output phase profile in each case, cleaned from the aberrations of coma, astigmatism, spherical aberration and trefoil. These findings were also contrasted with the results obtained without the diffractive OPC processor 10 between the two aberration planes – this resulted in non-uniform phase aberrations at the output plane, as expected. To better comprehend these results from an application standpoint, these output fields 110 were further focused through a diffraction-limited lens, the results of which are summarized in FIG. 9C. This aligns more closely with some of the existing practical applications where an OPC system is used to correct distorted wavefronts due to e.g., scattering media, enabling the conjugated wave to refocus through the same scattering medium again. The results reported in FIG. 9C clearly corroborate the diffractive OPC system's efficacy in achieving precise and sharp focusing. In contrast, in the absence of the diffractive OPC processor 10, apparent speckles can be found around the output focal point. These analyses further illustrate the efficacy of the diffractive OPC system, highlighting its potential applications for beam focusing through aberrations.

[0074] Optical phase conjugation of multi-wavelength illumination

[0075] The diffractive OPC processor model previously discussed was designed solely for operation at a single wavelength and was numerically demonstrated at the terahertz part of

the spectrum. In the following numerical analyses, designs of diffractive OPC processors 10 are presented that are capable of multispectral operation and demonstrate their efficacy within the visible spectrum (400-750 nm), where at each wavelength channel, the aberrated input wavefronts are independent of the other wavelength channels, representing a challenging broadband OPC task. As illustrated in FIGS. 17A, 17B, these multi-wavelength diffractive designs simultaneously perform phase conjugation of aberrated input wavefronts at N_w distinct wavelengths $\{\lambda_1, \lambda_2, \dots, \lambda_{N_w}\}$, uniformly distributed within a range of 400 nm to 750 nm. In these broadband diffractive OPC processor designs, $N_w = 2, 4, \text{ and } 8$ was used. Given this wavelength multiplexing task at hand, the total number of trainable diffractive features (N) in the OPC processor 10 was scaled proportionally with the number of wavelength channels (N_w) to maintain the information processing capability per channel. To analyze this behavior for each N_w choice, different OPC processors 10 were created with $N = \{0.5N_iN_oN_w, N_iN_oN_w, 2N_iN_oN_w\}$ and $K = 12$. Here, N_i and N_o represent the number of diffraction-limited pixels within the input and output apertures 32, 24, respectively. In these numerical analyses, N-BK7 glass was selected as the diffractive material due to its prevalent use for optical components at the visible band. The training data and methods used for these visible band diffractive OPC processor designs follow their terahertz counterparts. After the training, the diffractive layer thickness profiles corresponding to the model with $N = 2N_iN_oN_w$ and $N_w = 8$ wavelengths are visualized in FIG. 17B as an example.

[0076] To evaluate the performance of these diffractive multi-wavelength OPC processors 10, numerical blind testing was performed using input optical fields 100 with phase profiles composed of 2 random Zernike polynomials, which randomly varied at different wavelengths and were never used in the training. The average phase errors for all these diffractive OPC models with different N and N_w values are summarized in FIG. 18, revealing an error level of $<1.5\%$ for all the diffractive models. These results also indicate that introducing more degrees of freedom in the design (by increasing N) can substantially improve the phase accuracy of multispectral OPC operation; for example, for all the cases of $N_w = 2, 4$ and 8 , the average phase error is reported as $\sim 1.4\%$ when using $N = 0.5N_iN_oN_w$, which reduced to $\sim 1.0\%$ when using $N = 2N_iN_oN_w$. Exemplary multi-wavelength output fields from the diffractive OPC model using $N = 2N_iN_oN_w$ and $N_w = 8$ wavelengths are provided in FIG. 19A, demonstrating a decent match with their ground truth fields across all the eight wavelength channels. The same diffractive OPC model was tested with structurally more complex input fields composed of 3 random Zernike polynomials (never used in the training); as shown in FIG.

19B, the diffractive processor 10 still revealed output phase profiles that closely align with their ground truth across all the 8 wavelength channels. All these blind testing results corroborate the platform's feasibility for performing multi-wavelength OPC operations at different parts of the spectrum.

[0077] These multi-wavelength diffractive OPC designs shown on the left part of FIG. 18 employed N-BK7 as the diffractive layer material, which has a known dispersion curve with varying refractive index values as a function of the wavelength, which was numerically modeled in the diffractive designs. Next, the feasibility of constructing a broadband diffractive OPC processor 10 using a material with a different dispersion property was investigated; to highlight an extreme case, it was assumed a diffractive material with flat dispersion such that the refractive index does not change as a function of the wavelength within the operation band of interest. This dispersion-free material was selected to highlight an important feature of multispectral diffractive OPC designs: their phase conjugation performance at different wavelengths is independent of the material dispersion. Therefore, in this analysis, a diffractive material was adopted with flat dispersion, exhibiting a constant refractive index ($n=1.7$) within its operational band (400 nm to 750 nm). As reported on the right part of FIG. 18, these dispersion-free OPC diffractive designs achieve average phase errors of 1.34% and 0.95% across $N_w = 8$ wavelength channels when using $N = 0.5N_lN_oN_w$ and $2N_lN_oN_w$, respectively. Remarkably, they attain performance parity with previous designs that utilized N-BK7, even exhibiting a slight improvement. The output examples of the dispersion-free OPC processor design using $N = 2N_lN_oN_w$ and $N_w = 8$ wavelengths are also provided in FIGS. 20A, 20B, all presenting very good agreement with the ground truth. These findings confirm that the broadband OPC capability of the diffractive processors 10 is not subject to specific dispersion properties of the materials, thereby highlighting it as a versatile platform that can adapt to varying material choices and operation wavelengths.

[0078] Experimental validation of transmissive diffractive OPC networks

[0079] Next, the diffractive OPC framework was experimentally validated using a set-up based on monochromatic terahertz illumination. As illustrated in FIG. 10A, the objective here is to use a diffractive OPC processor 10 to perform phase conjugation of a wavefront, which is emitted by a pinhole-like object and subsequently distorted by a random, unknown phase perturbation plane. The resulting phase-conjugated wavefront (by the diffractive OPC processor) passes through another identical phase perturbation plane (P) to be refocused onto a small point – if the OPC was successful. In this experimental configuration, a diffractive

OPC design was used comprising $K=3$ phase-only dielectric diffractive layers 20 ($L_1 - L_3$), positioned between two identical random, unknown phase perturbation planes (P) with a phase contrast parameter of $\alpha_{\text{test}} = 0.5$. The input pinhole object is set as a square-shaped aperture 32 with a size of 4.3λ , situated at a distance d before the first random phase perturbation plane (P). The wavefront exiting the diffractive OPC processor 10 is expected to focus on a spot of the same size as the input object at the same distance d after the second phase perturbation plane (P). The intensity distribution of this focusing spot is measured at the output plane, with its quality serving as the figure-of-merit of this experimental OPC validation. The detailed structural parameters used for this experimental design are reported in FIG. 10A and the Methods section.

[0080] It is worth noting that, compared to the optical configuration used in the prior subsection (i.e., FIG. 9A), the experimental configuration in FIG. 10A possesses some differences. The main difference lies in that, in the experimental configuration, the optical field impinging onto the first phase perturbation plane (P) has a spherical wavefront emitted by a pinhole, rather than a uniform plane wave as the one in FIG. 10A. Therefore, the complex field i that enters the diffractive OPC system's aperture 32 after propagating through the first phase perturbation plane and the expected (ground truth) output complex field $o^{(\text{GT})}$ that exits from the diffractive OPC system before the second phase perturbation plane can be written as:

$$[0081] \quad i(x, y) = s(x, y)e^{j\Psi(x, y)} \quad (3),$$

$$[0082] \quad o^{(\text{GT})}(x, y) = i^*(x, y) = s^*(x, y)e^{-j\Psi(x, y)} \quad (4).$$

[0083] Here in Eqs. (3) and (4), Ψ denotes the phase profile of the randomly generated, unknown phase perturbation plane, and s represents the illumination field at the phase perturbation plane, emitted from the pinhole object. In the experimental set-up, due to the spherical wave characteristics of $s(x, y)$, both its amplitude and phase distributions exhibit an increasingly rapid change from the center outwards to the edges. This leads to a significantly larger phase contrast α_{test} in the actual input field. Therefore, if the diffractive OPC processor 10 can successfully retrieve (at the output plane) the image of the input (pinhole) object, despite the presence of the randomly generated phase aberrations, it would indicate the successful implementation of the diffractive system's phase conjugation capability.

[0084] To train the experimental OPC design using $K=3$ diffractive layers 20, a set of random phase perturbation planes (P) were generated and optimized the experimental

diffractive OPC design through deep learning. The phase profiles of the resulting three diffractive layers are visualized in the left column of FIG. 10B. These diffractive layers 20 were fabricated using 3D printing, with the photos of the fabricated diffractive layers 20 presented in the right column of FIG. 10B. After assembling these diffractive layers 20, a THz source ($\lambda = 0.75$ mm) and detector were used to measure the resulting intensity distribution at the output plane. The schematic and photographs of the experimental set-up are presented in FIGS. 10C and 10D.

[0085] During the experiments, the system was tested using four different phase perturbation planes (P) (also fabricated through 3D printing), which were never seen during the training ($\alpha_{\text{test}} = 0.5$). FIGS. 11A-11B show the experimental *measurements*, which successfully revealed a Gaussian-shaped circular spot pattern, closely aligning with the corresponding numerical simulation results. Furthermore, the system was also tested without placing the diffractive OPC processor 10 between the two-phase perturbation planes (P), i.e., with only free space propagation. The resulting experimental images displayed only scattered patterns, starkly contrasting with the results achieved using the diffractive OPC processor 10.

[0086] In addition to these experimental results, an ablation study was performed by constructing several baseline configurations and *comparing* their performances. As shown in FIG. 15A, these baseline configurations include replacing the three-layer diffractive OPC processor 10 with (1) a single-layer 20 diffractive OPC processor 10, (2) a conventional thin lens, and (3) free space. Here, the same phase perturbation planes (P) were used as in the experiments, but adjusted the phase contrast to $\alpha_{\text{test}} = 1$, which sets a more challenging test. After the training, the resulting thickness profiles of the diffractive layers 20 for these baseline configurations are provided in FIG. 15B, and their test results are compared in FIG. 16. From these comparative analyses, it can be found that the single-lens and the single-diffractive-layer 20 systems produce similar results: while they can both generate a spot at the output plane, the positions of the spots do not appear accurately at the center, revealing beam focusing artifacts, and these spots are accompanied by various noise patterns at the output plane. The results of the $K=3$ diffractive OPC processor 10, on the other hand, provide superior results to both of these baseline systems, as shown in FIG. 16. These observations also align with the architectural depth advantages of diffractive visual processors, demonstrated for various applications by achieving better approximation accuracy for a given task when the diffractive degrees of freedom are distributed across a deeper architecture.

[0087] Apart from the monochromatic diffractive OPC design reported above, experimental validation was also performed on a multi-wavelength OPC processor 10. Following the same architecture and training method used by the monochromatic model shown in FIGS. 10A-10D, a diffractive multi-wavelength OPC processor 10 was trained to simultaneously support phase conjugation operation at three distinct wavelengths: 0.75, 0.775 and 0.8 μm . The resulting diffractive layers were fabricated using 3D printing, as shown in FIG. 21A. In this experiment, the same input aperture 32 was used as in the previous test and sequentially illuminated the phase perturbation plane with each operational wavelength, capturing the corresponding intensity distribution within the output aperture 34. The experimental results, presented in FIG. 21B, show that the diffractive multi-wavelength OPC processor 10 consistently generated Gaussian-shaped circular output patterns for all three wavelengths, achieving similar results to its monochromatic counterpart shown in FIG. 11B. This success further substantiates the feasibility of designing diffractive OPC processors 10 capable of correcting broadband aberrated fields across multiple wavelength channels, with an independent aberration in each channel.

[0088] **Output power efficiency of diffractive OPC designs**

[0089] In traditional AOPC solutions, the *output* power of the phase-conjugated beam could be weak due to the nonlinear optical processes involved in AOPC systems, often leading to a low power efficiency of $<1\%$. While the digital OPC methods can provide considerable power due to incorporating active illumination and modulation in their playback process, they present other limitations, including increased system complexity and reduced operation speed. For the diffractive OPC framework, its power efficiency is directly associated with the output diffraction efficiency exhibited by the diffractive volume. Axially deeper diffractive wavefront processor architectures have proven advantageous in terms of their transformation accuracy and output diffraction efficiency. Here, the impact of the number of trainable diffractive layers 20 (K) on the OPC performance was quantified by the output phase MAE. Taking the design shown in FIG. 7B with $K = 8$ as the baseline design for this analysis, its counterparts were trained with different numbers of diffractive layers 20, e.g., $K = 4, 6$ and 10 , by maintaining the other structural parameters identical to the baseline design, also using the same training dataset. FIG. 12A reports these designs' resulting output phase MAE values as a function of K . It is evident that as K increases the phase conjugation errors of the diffractive output optical fields 110 decrease; for example, the phase MAE values at $K = 4$ and 10 are reported as $2.37 \pm 0.37\%$ and $1.55 \pm 0.21\%$, respectively. These

findings are also confirmed through the exemplary visualization results shown in FIG. 12B, where the output phase profiles from the models with $K = 8$ and 10 present much better similarity to their ground truth when compared to the models with smaller K . Furthermore, the output diffraction efficiencies of these OPC designs also present an increasing trend as more diffractive layers 20 are used. For instance, the model with $K = 4$ yields an output diffraction efficiency of $13.8 \pm 1.2\%$, and this efficiency increases to $24.4 \pm 1.2\%$ when $K = 10$ is used, marking an efficiency increase of 10.6%. These diffraction efficiency metrics underscore that a deeper architecture for the diffractive wavefront processors 10 achieves both better OPC performance and better output power efficiency by exploiting the larger degrees of freedom and the depth advantage.

[0090] Although the diffractive OPC designs shown in FIGS. 12A-12B all present output diffraction efficiencies of >13-25%, OPC systems that are even more power-efficient might be sought for various real-world applications, involving e.g., low signal-to-noise ratio image sensors. To address this need, one can introduce an additional diffraction efficiency-related loss term to the training loss function, aiming to balance the tradeoff between the OPC performance and the diffraction efficiency of the diffractive wavefront processor (see the Methods for details). This strategy was already employed in the experimental design shown in FIG. 10B to enhance the diffraction efficiency of the output signals. In FIGS. 13A-13B, an in-depth quantitative exploration of this tradeoff relationship between the OPC performance and the output diffraction efficiency is illustrated. For this analysis, the two designs with $K = 4$ and 8 shown in FIGS. 12A-12B were revisited; these designs respectively exhibit diffraction efficiencies of $13.8 \pm 1.2\%$ and $20.2 \pm 0.9\%$, with phase MAE values of $2.37 \pm 0.37\%$ and $1.71 \pm 0.21\%$, and amplitude MAE values of $10.80 \pm 2.13\%$ and $10.80 \pm 2.84\%$. Keeping the structural parameters identical as before and utilizing the same training/testing dataset, these diffractive OPC designs were retrained (from scratch) by applying varying degrees of diffraction efficiency penalty to the training loss functions, resulting in new designs with enhanced output diffraction efficiencies. FIG. 13A depicts the phase and amplitude MAE values of these new designs in relation to their output diffraction efficiencies. These results reveal that, compared to the original $K=4$ design shown in FIGS. 12A-12B, the newly trained diffractive designs achieved a ~6-fold increase in their output diffraction efficiencies, reaching up to $85.9 \pm 1.7\%$. This improvement comes with a modest sacrifice in their phase conjugation performance, with phase MAE values reaching up to $3.23 \pm 0.38\%$. Similarly, compared to the original $K = 8$ design shown in FIGS. 12A-12B, these

new designs subjected to the diffraction efficiency penalty showcased a further improved diffraction efficiency of up to $92.1 \pm 1.5\%$, with only marginal surges in the phase MAE values that reach up to $2.26 \pm 0.32\%$.

[0091] In these analyses, an intriguing phenomenon was observed: as the diffraction efficiency increases, there is a slight decrease in the amplitude MAE values of the diffractive OPC designs. These results suggest that a stronger diffraction efficiency-related penalty term results in a greater portion of the lower spatial frequency modes being directed into the output aperture 34, leading to a more uniform output field amplitude distribution, which lowers the amplitude MAE values. FIG. 13B offers a visual representation of these designs' diffractive output fields 110; providing further corroboration. Collectively, these results suggest that diffractive OPC processors 10 can provide a favorable balance between their phase conjugation performance and output diffraction efficiency, which can be improved as desired by using an appropriate training loss function.

[0092] Diffractive phase-conjugate mirror design

[0093] In the results and analyses presented so far, diffractive OPC processors 10 in a transmission geometry were used. While the transmissive structure illustrated can be retrofitted into a reflective OPC configuration such as FIG. 1B, this may complicate the system with additional optical components such as beam splitters and image projection systems. To create a simpler solution for designing a phase-conjugate mirror, a diffractive OPC system was merged with an ordinary reflective mirror (M), which creates a double-pass configuration through the same diffractive layers 20 to all-optically perform OPC in reflection mode. As illustrated in FIG. 14A, the incident phase aberrated field, denoted as $\mathbf{i} = e^{j\psi}$, first propagates through the diffractive layers 20 ($L_1, \dots, L_K$), resulting in an intermediate field $\mathbf{o}^{(\text{intermediate})} = \text{D}^2\text{NN}_{\text{forward}}\{e^{j\psi}\}$. Upon reflection from the planar mirror (M), this reflected intermediate field (i.e., $R\{\mathbf{o}^{(\text{intermediate})}\}$) traces its path in the reverse direction across the same set of diffractive layers 20, ultimately collected in reflection through the same aperture 32 used for input. This produces a final reflected output field $\mathbf{o} = \text{D}^2\text{NN}_{\text{backward}}\{R\{\mathbf{o}^{(\text{intermediate})}\}\}$, i.e., $\mathbf{o} \approx \alpha \cdot \mathbf{o}^{(\text{GT})} = \alpha \cdot \mathbf{i}^* = \alpha \cdot e^{-j\psi}$.

[0094] Following this optical configuration, a diffractive phase-conjugate mirror was numerically modeled that shares the same set of design parameters as the previous transmissive OPC design presented in FIG. 7A. Utilizing the same dataset used by the analysis reported in FIGS. 7A-7E, the diffractive model was trained and validated, with the resulting phase profiles of the diffractive layers 20 shown in FIG. 22. Numerical simulations

achieved average phase and amplitude MAE values across different test sets: for input phase profiles constituted by two randomly selected Zernike polynomials, the phase and amplitude MAE values were $1.25 \pm 0.05\%$ and $9.41 \pm 2.87\%$, respectively; for those input fields using a single randomly selected Zernike polynomial, the MAE values were $1.31 \pm 0.07\%$ and $11.10 \pm 3.93\%$, respectively; and for those featuring three randomly selected Zernike polynomials, the MAE values were $1.25 \pm 0.04\%$ and $7.92 \pm 2.20\%$, respectively. Moreover, the visual illustrations reported in FIGS. 14C-14E revealed that the diffractive output optical fields 110 present a very good agreement with their corresponding ground truth phase profiles, confirming the success of the OPC operation. The amplitude distributions of the reflected fields also generally retain uniformity with minor errors that stand at a similar level as the previous transmissive OPC designs. Overall, these results affirm the feasibility of designing a diffractive OPC processor 10 coupled with an ordinary mirror (M) to create a reflective phase-conjugate mirror, which might find various applications in e.g., turbidity suppression and atmospheric aberration correction, among many others.

[0095] Discussion

[0096] The generation of phase-conjugated output fields 110 using diffractive OPC processors 10 was successfully demonstrated. Nonetheless, some imperfections can be observed in the output amplitude profiles, especially in the reflective design of the diffractive phase-conjugate mirror. These non-uniformity-related errors in the output amplitude profiles can be mitigated and suppressed by adjusting the hyperparameter that governs the amplitude uniformity penalty in the training loss function. To highlight this opportunity, further analysis of this amplitude non-uniformity is seen in FIG. 14B based on the transmissive and reflective designs presented in FIG. 7B and FIG. 22, respectively, utilizing input fields composed of two randomly selected Zernike polynomials. By changing the penalty threshold (V) associated with the level of non-uniformity in the output amplitude field, different OPC processors 10 were designed and plotted the corresponding changes in the average phase MAE values against the average amplitude MAE values. Notably, for the transmissive design, the amplitude error decreased from $8.89\% \pm 2.04\%$ to $4.51\% \pm 0.76\%$, alongside a relatively small phase error increase from $1.38 \pm 0.12\%$ to $1.97 \pm 0.15\%$. A similar pattern is also observed for the reflective OPC designs, with the amplitude error dropping from $9.41 \pm 2.23\%$ to $4.60 \pm 0.78\%$ and the phase error rising from $1.25 \pm 0.11\%$ to $1.67 \pm 0.13\%$. These results indicate that more uniform amplitude profiles can be achieved at the output aperture 34 of the diffractive OPC processors 10 with only a minor compromise in output phase

accuracy. Moreover, the analysis suggests that reflective designs outperform their transmissive counterparts in terms of both amplitude and phase errors, which can be attributed to their double-pass configuration that more efficiently exploits the available degrees of freedom within the diffractive volume. These findings are further supported by the visualization examples provided in FIGS. 23A and 23B, showing enhanced amplitude uniformity when the amplitude penalty threshold (V) is adjusted.

[0097] To better understand the diffractive OPC models' generalization capability, the complexity of the test data was deliberately increased by generating input phase profiles with ≥ 3 Zernike polynomials, introducing phase structures that are spatially more complex, exhibiting rapid variations. This blind testing evaluation was conducted using the same diffractive phase-conjugate mirror model that was originally trained on phase profiles constructed from two randomly selected Zernike polynomials. The results of this evaluation, demonstrated in FIG. 24A, reveal that the diffractive OPC processor 10 maintained high accuracy levels, with phase errors remaining $<1.3\%$ across input datasets incorporating 3 to 8 randomly selected Zernike polynomials. Furthermore, the examples of the output fields, depicted in FIGS. 24B-24D, showcase very good concordance with their corresponding targets. These results highlight the OPC processor's versatility and effectiveness, affirming its capability to accurately handle a broad range of wavefront patterns, including various highly structured phase distortions and aberrations (never seen before). This underscores the utility of the presented platform as a general-purpose optical phase conjugation device.

[0098] In the practical implementations of the diffractive OPC processors 10, mechanical misalignment between different elements could constitute a notable challenge to their phase conjugation performance, as they can cause the optical waves to be modulated by the diffractive layers in an undesired way, leading to results deviating from their designed performance. To provide further evidence for this, the diffractive OPC processor model previously shown in FIG. 7A was used and subjected the diffractive layers to different magnitudes of random displacements, either in the lateral directions ($\Delta_x, \Delta_y \in U[-\Delta_{xy, \text{test}}, \Delta_{xy, \text{test}}]$) or the axial direction ($\Delta_z \in U[-\Delta_{z, \text{tr}}, \Delta_{z, \text{tr}}]$), sampled from random uniform distributions (U). The resulting OPC performances of these misaligned diffractive processors are summarized in FIGS. 25A, 25B, 26A, 26B, which reveal a clear trend of increasing degradation in both the amplitude and phase errors as the misalignment gets more severe. To address this misalignment challenge, a "vaccination" strategy can be applied during the training process by modeling these misalignment errors as random noise into the

numerical forward model of the system. Specifically, the 3D random displacements of the diffractive layers (Δ_x , Δ_y and Δ_z) can be modeled using random variables, changing from iteration to iteration during the training process, to provide substantial resilience against such random displacements at a tolerable cost of performance loss. The efficacy of this vaccination-based design strategy is demonstrated in FIGS. 25A, 25B, 26A, 26B, where new diffractive OPC processor models were trained under random lateral and axial misalignments of varying magnitudes. These vaccinated diffractive OPC processor results (shown in identified curves) reveal that if the training parameters $\Delta_{xy,tr}$ and $\Delta_{z,tr}$ encompass the range of misalignments encountered in the blind testing ($\Delta_{xy,test}$ and $\Delta_{z,test}$), the impact of such physical/random misalignments on OPC performance can be significantly reduced. For instance, compared to the baseline model that was not “vaccinated” against these misalignments, the average output phase error of the “vaccinated” model trained using $\Delta_{xy,tr} = 0.24\lambda$ is reduced to 3.30% when tested with $\Delta_{xy,test} = 0.24\lambda$. Visual analyses reported in FIGS. 27A, 27B and 28A, 28B further corroborate these findings, showing that the diffractive processor maintains high OPC output accuracy under different levels of misalignments, even when using structurally more complex aberrated input fields that are formed by a greater number of Zernike polynomials, as illustrated in FIGS. 27A, 27B and 28A, 28B. These results highlight the diffractive OPC processor’s capability to accommodate various phase aberration patterns and withstand unexpected random 3D misalignments among the diffractive layers 20. It is also possible to adopt the same vaccination strategy to mitigate the impact of rotational misalignments between the diffractive layers 20 when such misalignments become a critical factor in experiments. Specifically, in-plane rotations of the diffractive layers 20 can be modeled with 2D coordinate transformations based on unitary rotation matrices, and the out-of-plane rotations can be accounted for by adjusting the wave propagation forward model between randomly tilted diffractive planes. Beyond such mechanical misalignments in 3D, this vaccination strategy can also be extended to counteract other types of potential errors, such as fabrication imperfections in diffractive layers 20, inaccuracies in material dispersion characterization and detection noise, thereby enhancing the practical robustness of the diffractive OPC system.

[0099] The presented diffractive OPC processor designs offer significant advantages with their multi-wavelength operation, distinctly setting them apart from conventional OPC methods. While conventional AOPC systems are typically limited to narrowband operation due to their dependency on wavelength-specific nonlinear coefficients of materials, the

diffractive OPC processors 10 employ basic dielectric materials without the need for a specific dispersion relationship (see FIG. 18). The diffractive designs allow for multi-wavelength OPC operations, facilitating efficient performance over a wider spectral range, independent from the dispersion characteristics of the diffractive materials. For example, a broadband diffractive OPC processor 10 designed using N-BK7, a widely used borosilicate glass known for its high damage threshold and superior optical quality, is disclosed making it well-suited for a vast spectrum of wavelengths in the visible. In applications that demand a higher damage threshold, fused silica emerges as a viable alternative for the diffractive layer material, with UV to near-infrared band transmission and negligible thermal expansion.

[00100] Another key benefit of the framework is its exceptionally fast response time, performing OPC at the speed of light propagation, a feature paramount for numerous wavefront shaping (WFS) applications. An optimal WFS technique for scattering suppression would need to combine rapid system response, power efficient generation of the conjugated wave, and extensive degrees of freedom for precise wave manipulation. Speed is especially crucial for WFS, as it must be accomplished within the speckle correlation period, typically <1 ms, to be compatible with the dynamic nature of various specimens, such as living organisms and tissue samples. This requirement poses a challenge for conventional DOPC methods due to inherent delays in their operation. In contrast, the presented diffractive OPC processor, being entirely optical, achieves OPC operation as the light is transmitted through a thin optical volume, thus effortlessly satisfying the crucial demand for rapid response. To shed more light on this, the optical response time was calculated of the transmissive OPC processors 10 following the same design illustrated in FIG. 7B. Here, the response time is determined by the light propagation time throughout the entire diffractive volume (from the input plane to the output plane), encompassing all the free space propagation between the layers as well as within the diffractive layer materials. Specifically, with an axial spacing of 12λ between successive layers and a base thickness of 0.2 mm for each diffractive layer, the OPC response times can be calculated as ~ 293 ps and ~ 123 ps at $\lambda = 0.75$ μm and $\lambda = 0.3$ μm , respectively. For the diffractive phase conjugate mirror designs, which entail a double-pass configuration, the optical response times will be doubled compared to their transmissive counterparts. For diffractive OPC designs operating at the visible and IR part of the spectrum, for example, the optical response times will be further reduced by more than one order of magnitude as the thickness of the diffractive processor volume can be significantly reduced due to the shorter wavelength. This significant speed advantage compared to existing AOPC

and DOPC systems reported in the literature underscores the utility of these diffractive designs for applications that necessitate ultra-fast OPC response. Furthermore, by incorporating a diffraction efficiency penalty in the training loss function and enhancing the system's degrees of freedom through an increased number of diffractive features, this method holds the potential of achieving even higher power efficiency (see e.g., FIGS. 12A-12B and 13A-13B), also broadening the scope of operation beyond the limits of traditional OPC methods. These advantages render this framework particularly well suited for applications in biomedical imaging and potentially for astronomical observations through scattering media such as the atmosphere, where energy efficiency is critically important.

[00101]

[00102] The results and analyses herein have successfully demonstrated diffractive OPC processors 10 that can all-optically perform phase conjugation of input complex fields with arbitrary unknown phase distributions, without the need for any digital computation, image acquisition or active beam modulation. Through simulations, the accuracy of the diffractive OPC operation was analyzed, revealing the empirical relationship between the phase conjugation accuracy and the phase contrast of the input fields. Furthermore, this concept at the terahertz part of the spectrum was experimentally validated by 3D fabricating a diffractive OPC processor 10, which successfully processed randomly generated phase-aberrated input optical fields 100. The presented diffractive OPC processor designs can be scaled (expanded/shrunk) to extend their operation to other parts of the electromagnetic spectrum, including the visible and IR bands, mm-wave, or x-ray range. Such diffractive OPC processors 10 operating at shorter wavelengths can be fabricated using appropriate nano-/micro-fabrication methods, such as two-photon polymerization-based 3D fabrication.

[00103] **Methods**

[00104] **Optical forward model of the diffractive OPC processors**

[00105] To model a diffractive OPC processor 10, its diffractive layers 20 are treated as thin planar elements that modulate the complex field of the incident coherent light. For the q^{th} diffractive feature of the l^{th} layer positioned at the spatial coordinates (x_q, y_q, z_l) , the complex transmission coefficient $t(x_q, y_q, z_l)$ can be represented as a function of its material thickness h_q^l . This relationship can be mathematically expressed as:

[00106]
$$t(x_q, y_q, z_l) = \exp\left(\frac{-2\pi\kappa h_q^l}{\lambda}\right) \exp\left(\frac{-j2\pi(n-n_{\text{air}})h_q^l}{\lambda}\right) \quad (5).$$

[00107] Here, n and κ correspond to the refractive index and extinction coefficient of the selected dielectric material at λ , corresponding to the real and imaginary components of the complex refractive index $\tilde{n}$, i.e., $\tilde{n} = n + j\kappa$. For the diffractive OPC designs used for experimental validation, n and κ were set using a terahertz spectroscopy system. In the other diffractive OPC designs used for numerical analyses at a single wavelength in the terahertz spectrum, the refractive index n was set as 1.7, while κ was chosen as 0. For the diffractive multi-wavelength OPC designs shown in FIG. 17B, the refractive index profile $n(\lambda)$ was set based on the dispersion of N-BK7 glass. $\kappa(\lambda)$ was set to 0, as the absorption of this material within the visible spectrum is negligible. For each diffractive feature, the thickness value h is composed of two parts: a constant h_{base} that serves as the substrate support and a variable $h_{\text{learnable}}$, i.e.,

$$[00108] \quad h = h_{\text{learnable}} + h_{\text{base}} \quad (6)$$

[00109] where $h_{\text{learnable}}$ represents the learnable thickness value of each diffractive feature 22 and is constrained within the range $[0, h_{\text{max}}]$. For the diffractive design shown in FIG. 7B, h_{max} is set as 1.07 mm, covering a full phase modulation range from 0 to 2π for $\lambda = 0.75$ mm. h_{base} is empirically chosen as 0.2 mm to provide the substrate (mechanical) support for the diffractive features. For the diffractive multi-wavelength OPC design shown in FIG. 17B, h_{max} is set as 1465 nm, ensuring complete phase modulation coverage, ranging from 0 to 2π , for the longest wavelength (λ_{N_w}). h_{base} is empirically chosen as 200 nm.

[00110] The band-limited angular spectrum approach was used to simulate the free-space propagation of coherent optical fields between the diffractive layers, where the resulting field is subsequently modulated by the transmittance $t(x, y, z_{l+1})$ of the $(l+1)^{\text{th}}$ diffractive layer 20. This process can be written as:

$$[00111] \quad u_p^{l+1}(x, y, z_{l+1}) = t(x, y, z_{l+1}) \mathcal{F}^{-1} \{ \mathcal{F} \{ u_q^l(x, y, z_{l+1}) \} H_q^l(f_x, f_y, d_m) \} \quad (7),$$

[00112] where $\mathcal{F}\{\cdot\}$ and $\mathcal{F}^{-1}\{\cdot\}$ denote the 2D fast Fourier transform and the inverse 2D fast Fourier transform operations, respectively, and $H_q^l(f_x, f_y, d_m)$ is the transfer function of free-space propagation with a distance d_m between two successive diffractive layers 20, which is given by:

$$[00113] \quad H_q^l(f_x, f_y, d) = \begin{cases} \exp \left\{ \frac{j2\pi d_m}{\lambda} \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right\}, & f_x^2 + f_y^2 < \frac{1}{\lambda^2} \\ 0, & f_x^2 + f_y^2 \geq \frac{1}{\lambda^2} \end{cases} \quad (8),$$

[00114] where f_x and f_y represent the spatial frequencies along the x and y directions, respectively.

[00115] For numerical simulations of the diffractive OPC designs in the terahertz spectrum, the spatial sampling rate of the simulated complex fields is set as 0.4 mm, i.e., $\sim 0.53\lambda$. The lateral dimension of the individual diffractive features 22 on the diffractive layers 20 was also set as 0.4 mm. As for the numerical simulations of the broadband diffractive designs in the visible spectrum, the spatial sampling rate for simulating the complex fields and the lateral dimension of diffractive features were both selected as 200 nm, i.e., $\sim 0.35\lambda_m$. The axial spacing between the adjacent layers 20 (including the diffractive layers 20 and input/output planes) was selected as 12λ for the numerical design shown in FIG. 6A and 20λ for the experimental validation design shown in FIG. 10A and $20\lambda_m$ for the multi-wavelength numerical designs shown in FIG. 17B.

[00116] Numerical implementation of the diffractive OPC processors and phase-conjugate mirrors

[00117] In the diffractive OPC network design, a phase-only object is set to be positioned at $z = z_0$, featuring a phase profile $\Psi(x, y)$ and uniform distribution of unit amplitude. This object is illuminated by a coherent, uniform plane wave, generating an input complex field i that can be mathematically described as:

[00118]
$$i(x, y) = e^{j\Psi(x, y)} \quad (9)$$

[00119] Here i can also be denoted as u^1 , i.e., $u^1(x, y, z_0) = e^{j\Psi(x, y)}$. Subsequently, as the input light propagates through the diffractive network volume, the input field i (or u^1) is subject to a series of diffractive layer modulations and secondary wave formations detailed in the last subsection, ultimately resulting in an output complex field $o(x, y) = u^K(x, y, z_K)$.

[00120] For the diffractive OPC processor 10 design depicted in FIG. 7A, both the input and output apertures 32, 24 are designed to have a circular shape with a diameter of $\sim 59.36\lambda$. The input/output apertures 32, 34 are discretized into 560 pixels, i.e., $N_i = N_o = 560$, with each measuring a size of $\sim 2.12\lambda \times 2.12\lambda$. To ensure the successful execution of the desired OPC task, each diffractive layer 20 within this diffractive OPC processor 10 is designed to contain 200×200 diffractive features 22, spanning an area of $\sim 106\lambda \times 106\lambda$. For the experimental design shown in FIG. 10A, the input and output apertures 32, 34 are square-shaped and share identical dimensions of $\sim 29.68\lambda \times 29.68\lambda$. The input/output apertures 32, 34 are sampled into arrays of 28×28 pixels, leading to an individual pixel size of $\sim 1.06\lambda \times$

1.06λ . The diffractive layers 20 in this design contain 120×120 diffractive features 22 (for each layer 20), spanning an area of $\sim 64\lambda \times 64\lambda$.

[00121] For the diffractive phase-conjugate mirror design illustrated in FIG. 14A, the settings of the input/output apertures 32, 34 and the diffractive layers 20 align with those of the diffractive OPC processor 10 design depicted in FIG. 7A. The main change in this set-up is the integration of a standard mirror (M) placed to the right of the diffractive layers 20, and the output aperture 34 coincides with the location of the input aperture 32 ($z = z_0$), allowing OPC processor 10 to operate in reflection mode. In the numerical simulation, a π phase shift was introduced at the standard mirror reflection.

[00122] For the $N_w = 8$ diffractive multi-wavelength OPC processor 10 shown in FIG. 17B, the input and output apertures 32, 34 are designed to have a circular shape with a diameter of $\sim 38.92\lambda_m$. The input/output apertures 32, 24 are discretized into 560 pixels, i.e., $N_i = N_o = 560$, with each pixel measuring a size of $\sim 1.39\lambda_m \times 1.39\lambda_m$. Each diffractive layer 20 within this diffractive OPC network 10 is designed to contain 646×646 diffractive features, spanning an area of $\sim 225\lambda_m \times 225\lambda_m$. Other multispectral designs analyzed in FIG. 18 use a similar architecture but vary by including different numbers of diffractive features 22 within their diffractive layers 20.

[00123] Training loss function and performance metrics

[00124] The primary objective of training a diffractive OPC processor 10 is to ensure that its diffractive output optical field 110 exhibits a phase distribution that is the conjugate of its input optical field 100 counterpart, while concurrently maintaining a uniform amplitude distribution identical to that of the input field. Due to the power loss of the optical field that occurs during its propagation through the diffractive volume, it is necessary to normalize the output field in the training and evaluation process to ensure that the calculated errors and metrics are not influenced by the output diffraction efficiency. Additionally, when quantifying the phase conjugation-related errors, it is necessary to eliminate the influence of the phase offset (overall constant phase difference) that might exist between the output phase profile and the ground truth. In this regard, a normalization strategy was adopted for the diffractive output fields and the corresponding ground truth, which are given by:

[00125]
$$\hat{\mathbf{o}} = \sigma \mathbf{o} \quad (10),$$

[00126]
$$\hat{\mathbf{o}}^{(\text{GT})} = \sigma^{(\text{GT})} \mathbf{o}^{(\text{GT})} \quad (11),$$

[00127] where $\sigma^{(\text{GT})}$ and σ are the normalization factors, given by:

[00128]
$$\sigma^{(\text{GT})} = \frac{1}{\sqrt{\sum_{(x,y) \in \mathcal{S}} |o^{(\text{GT})}(x,y)|^2}} \quad (12),$$

[00129]
$$\sigma = \frac{\sum_{(x,y) \in \mathcal{S}} \sigma^{(\text{GT})} o^{(\text{GT})}(x,y) o^*(x,y)}{\sum_{(x,y) \in \mathcal{S}} |o(x,y)|^2} \quad (13).$$

[00130] Based on these normalized quantities constructed above, a custom training loss function $\mathcal{L}$ was devised to achieve a balance between the phase conjugation loss term $\mathcal{L}_{\text{OPC}}$ and an amplitude uniformity-related loss term $\mathcal{L}_{\text{Amp}}$ (for a single wavelength channel) which can be written as:

[00131]
$$\mathcal{L} = \mathcal{L}_{\text{OPC}} + \beta_{\text{Amp}} \mathcal{L}_{\text{Amp}} \quad (14).$$

[00132] Herein, β_{Amp} denotes the weight coefficient associated with $\mathcal{L}_{\text{Amp}}$ and is empirically selected as 1 during the training of all the designs presented herein. The phase conjugation loss term $\mathcal{L}_{\text{OPC}}$ penalizes the MAE between the phase profile of the normalized diffractive output field $\angle \hat{\mathbf{o}}$ and its ground truth $\angle \hat{\mathbf{o}}^{(\text{GT})}$, which can be written as:

[00133]
$$\mathcal{L}_{\text{OPC}} = \frac{1}{N_{\mathcal{S}}} \sum_{(x,y) \in \mathcal{S}} |\angle \hat{\mathbf{o}}^{(\text{GT})}(x,y) - \angle \hat{\mathbf{o}}(x,y)| \quad (15),$$

[00134] where $\mathcal{S}$ denotes the output aperture 34 and $N_{\mathcal{S}}$ represents the total number of pixels within $\mathcal{S}$. The amplitude uniformity loss term $\mathcal{L}_{\text{Amp}}$ is defined as:

[00135]
$$\mathcal{L}_{\text{Amp}} = \max(V, \mathcal{L}_{\text{AmpMSE}}) - V \quad (16),$$

[00136] where $\mathcal{L}_{\text{AmpMSE}}$ stands for the normalized mean square error (MSE) between $|\hat{\mathbf{o}}|$ and its ground truth $|\hat{\mathbf{o}}^{(\text{GT})}|$, which can be written as:

[00137]
$$\mathcal{L}_{\text{AmpMSE}} = \frac{1}{N_{\mathcal{S}}} \sum_{(x,y) \in \mathcal{S}} \left| |\hat{\mathbf{o}}^{(\text{GT})}(x,y)| - |\hat{\mathbf{o}}(x,y)| \right|^2 \quad (17).$$

[00138] In Eq. (16), V is a predetermined threshold used to determine when to start penalizing $\mathcal{L}_{\text{AmpMSE}}$. Stated differently, the amplitude uniformity penalty is effective only when $\mathcal{L}_{\text{AmpMSE}} > V$. For all the diffractive models disclosed herein, the value of V was empirically chosen as 0.02.

[00139] In the experimental validation and the output diffraction efficiency-related analyses, a modified loss function was employed by further adding an output diffraction efficiency-related loss term, $\mathcal{L}_{\text{Eff}}$, into the original loss function defined in Eq. (14), which is given by:

[00140]
$$\mathcal{L} = \mathcal{L}_{\text{OPC}} + \beta_{\text{Amp}} \mathcal{L}_{\text{Amp}} + \beta_{\text{Eff}} \mathcal{L}_{\text{Eff}} \quad (18),$$

[00141] where β_{Eff} denotes the weight coefficient associated with $\mathcal{L}_{\text{Eff}}$. $\mathcal{L}_{\text{Eff}}$ is defined as:

[00142]
$$\mathcal{L}_{\text{Eff}} = e^{-\gamma\eta} \quad (19),$$

[00143] where γ is an empirical weight coefficient. During the training of the experimental model, the values of β_{Eff} and γ were set as 1 and 100, respectively; for the diffractive models trained with output diffraction efficiency penalty shown in FIG. 13A, the values of γ were selected as 30, 20, 10, 5, and the value of β_{Eff} was constantly chosen as 1. η represents the output diffraction efficiency and is defined as:

[00144]
$$\eta = \frac{\sum_{(x,y) \in \mathcal{S}} |o(x,y)|^2}{\sum_{(x,y) \in \mathcal{S}} |i(x,y)|^2} \quad (20).$$

[00145] For the optimization of a diffractive multi-wavelength OPC design, a loss function was used that averages the loss values for different wavelength channels computed using Eq. (14) (or Eq. (18) when the power efficiency-related penalty is used). The resulting loss function $\mathcal{L}_{\text{total}}$ is given by:

[00146]
$$\mathcal{L}_{\text{total}} = \frac{1}{N_w} \sum_{w=1}^{N_w} \alpha_w \mathcal{L}_w \quad (21),$$

[00147] where α_w represents the weight coefficient associated with the loss calculated from the w^{th} wavelength channel of the diffractive multispectral OPC processor 10. Throughout the training process, the values of α_w , all initialized as 1, were dynamically updated after each epoch, guided by the comparative loss magnitudes across the different wavelength channels to achieve a balanced spectral response. This adjustment equation for α_w is expressed as:

[00148]
$$\alpha_w \leftarrow \max(0.1 \times (\mathcal{L}_w - \mathcal{L}_{\text{mean}}) + \alpha_w, 0) \quad (22),$$

[00149] where $\mathcal{L}_{\text{mean}}$ represents the mean loss across all the wavelength channels. Under this training approach, a wavelength channel with a loss exceeding the average will see an increase in its α_w , thereby raising its balance weight and intensifying the penalty on its output performance.

[00150] For evaluating the phase conjugation performance of the presented diffractive OPC processor 10, the mean absolute errors of diffractive output amplitude profiles and the diffractive output phase profiles were calculated, defined as:

[00151]
$$MAE_{\text{Amp}} = \frac{1}{N_s} \sum_{(x,y) \in \mathcal{S}} ||\hat{o}^{(\text{GT})}(x,y)| - |\hat{o}(x,y)|| \quad (23),$$

[00152]
$$MAE_{\text{Phase}} = \frac{1}{N_s \Delta_{\text{test}} \pi} \sum_{(x,y) \in \mathcal{S}} |\angle \hat{o}^{(\text{GT})}(x,y) - \angle \hat{o}(x,y)| \quad (24).$$

[00153] Here, the testing phase contrast parameter α_{test} is used to normalize the phase error with regard to the dynamic range of the input phase contrast. Therefore, the error metric MAE_{phase} reveals a relative difference between the diffractive output phase profiles and their ground truth.

[00154] **Details of the experimental diffractive OPC system**

[00155] For the experimental set-up, a diffractive OPC processor 10 was designed composed of three isotropic, phase-only diffractive layers 20 ($L_1 - L_3$) between two identical random unknown phase perturbation planes (P) with a phase contrast parameter of $\alpha_{\text{test}} = 0.5$, axially spanning a distance of 80λ from the first phase perturbation plane (P) to the second phase perturbation plane (P), with a distance d_m of 20λ between successive diffractive layers 20. At the system's forefront, a square-shaped aperture 32 was placed with a width of $\sim 4.3\lambda$, serving as a small pinpoint object $\tilde{t}$. This initiates an input wavefront similar to a spherical wave, which travels a distance (d) of $\sim 266\lambda$ and subsequently encounters a random, unknown phase perturbation plane (P) with 28×28 pixels. The illustrative design is shown in FIG. 10A.

[00156] To optimize the diffractive OPC processor 10 shown in FIG. 10B, a training dataset was created comprised of 50,000 randomly generated phase perturbation planes (P). Each of these planes (P) was conceptualized as a phase-only mask, with complex transmission coefficients, $t_p(x, y)$, defined as:

$$[00157] \quad t_p(x, y) = \exp\left(j \frac{2\pi\Delta n}{\lambda} P(x, y)\right) \quad (25).$$

[00158] The random height map $P(x, y)$ is defined as:

$$[00159] \quad P(x, y) = V(x, y) * K(\sigma) \quad (26),$$

[00160] where $V(x, y)$ follows a normal distribution with a mean μ and a standard deviation σ_0 , i.e.,

$$[00161] \quad V(x, y) \sim N(\mu, \sigma_0^2) \quad (27),$$

[00162] $K(\sigma)$ represents a Gaussian smoothing kernel with zero mean and a standard deviation of σ . The symbol “*” stands for the 2D convolution operation. Throughout this application, $\mu = 25\lambda$, $\sigma_0 = 4\lambda$, and $\sigma = 8\lambda$ were used for the generation of the 50,000 random phase perturbation planes (P). Given these settings, the resulting average correlation

length of phase perturbation can be calculated as $L \sim 14.7\lambda$ using a phase autocorrelation function.

[00163] As shown in FIG. 10C, a terahertz continuous wave (CW) system was used to test the diffractive OPC processor 10 design. In this system, a terahertz source was used as the light source 12, consisting of a modular amplifier/multiplier chain (AMC) (Virginia Diode Inc. WR9.0M SGX/WR4.3x2 WR2.2x2), coupled with a compatible diagonal horn antenna (Virginia Diode Inc. WR2.2). A 10-dBm radiofrequency (RF) input signal was generated at a frequency of 11.1111 GHz (fRF1) at the input of the AMC and was then multiplied by 36 times to generate the output CW radiation at 0.4 THz, corresponding to a wavelength of 0.75 mm. Also, the AMC output was modulated with a 1-kHz square wave for lock-in detection. The 4-mm-width input aperture 32 was positioned ~ 50 mm away from the exit aperture 34 of the horn antenna. The intensity distribution within the output aperture 34 was 2D-scanned at a step size of 0.8 mm by a single-pixel mixer (Virginia Diode Inc. WRI 2.2), which was mounted on an XY positioning stage constructed using two Thorlabs NRT100 motorized stages. A 10-dBm RF signal at 11.0833 GHz (fRF2) was also received by the detector to serve as the local oscillator to down-convert the output frequency to 1 GHz. This down-converted signal was then amplified using a low-noise amplifier (Mini-Circuits ZRL-1150-LN+) with a gain of 80 dBm and filtered through a bandpass filter at 1 GHz (± 10 MHz) (KL Electronics 3C40-1000/T10-O/O), which mitigate the noise resulted from unwanted frequency bands. After the signal went through a tunable attenuator (HP 8495B) for linear calibration, it was then processed by a low-noise power detector (Mini-Circuits ZX47-60). The resulting output voltage from the detector was measured using a lock-in amplifier (Stanford Research SR830), where the 1-kHz square wave was used as the reference signal for calibration into a linear scale. The same system was also used to test the diffractive multi-wavelength OPC processor design, where the CW radiation was set to operate at the wavelengths of 0.75 mm, 0.775 mm and 0.8 mm.

[00164] For the fabrication of the resulting diffractive OPC processor 10, a 3D printer (Objet30 Pro, Stratasys) was used to fabricate the diffractive layers 20 shown in FIG. 10B and FIG. 21B. The phase perturbation planes (P) and the input aperture 32 were also 3D printed using the same printer (Objet30 Pro, Stratasys). To achieve alignment in accordance with the optical forward model of the experimental diffractive design, a 3D-printed holder 30 was utilized to assemble the input aperture 32, the phase perturbation planes and the printed diffractive layers, ensuring their precise 3D positioning.

[00165] Training and numerical implementation details

[00166] The numerical modeling and training of the diffractive OPC designs presented herein were implemented using Python (v3.7.13) and PyTorch (version 1.12.1, Meta Platform Inc.). The Adam optimizer was selected with the default parameters in PyTorch for optimizing the trainable parameters, i.e., the phase modulation coefficients of the diffractive layers 20. For all the models presented herein, the training underwent 100 epochs, with the batch size set as 128. Starting from an initial value of 0.001, the learning rate was set to decay at a rate of 0.5 every 10 epochs. These diffractive models were trained using a workstation with an Nvidia GeForce RTX 3090 GPU, an Intel Core i9-11900 CPU and 128 GB of RAM. The training of an 8-layer diffractive OPC design typically took ~20 hours.

[00167] While embodiments of the present invention have been shown and described, various modifications may be made without departing from the scope of the present invention. For example, in one embodiment, the input optical field 100 has optical field components spanning a plurality of wavelengths and the resulting output optical fields 110 possess respective phase distributions that are individually conjugates of the input optical field components at the plurality of wavelengths as noted herein. The invention, therefore, should not be limited, except to the following claims, and their equivalents.

What is claimed is:

1. A diffractive wavefront processor for performing optical phase conjugation (OPC) on an input optical field comprising:

one or more optically transmissive and/or reflective layers arranged in an optical path, each of the one or more optically transmissive and/or reflective substrate layers comprising a plurality of physical features formed on or within the one or more optically transmissive or reflective substrate layers and having different transmission and/or reflection properties as a function of the lateral coordinates across each layer, wherein the one or more optically transmissive and/or reflective substrate layers modulate the input optical field to generate an output optical field with a phase distribution that is the conjugate of the input optical field; and

wherein the one or more optically transmissive and/or reflective substrate layers are designed during a training process with a plurality of input phase distributions and their corresponding conjugated versions to optimize the plurality of physical features formed on or within the one or more optically transmissive or reflective substrate layers to perform OPC on the input optical field.

2. The diffractive wavefront processor of claim 1, wherein the input optical field is in a mm-wave, THz, infrared, visible, or x-ray range of the electromagnetic spectrum.

3. The diffractive wavefront processor of claim 1, wherein the input optical field has a phase profile representing different optical aberrations comprising one or more of coma, astigmatism, spherical aberration, and/or trefoil.

4. The diffractive wavefront processor of claim 1, wherein the input optical field comprises an optical field passing through turbid media, diffuser(s), or scatterer(s).

5. The diffractive wavefront processor of claim 1, further comprising a mirror disposed along the optical path and after the one or more optically transmissive and/or reflective layers to perform OPC in reflection geometry, where the conjugated output optical field is reflected back and appears at an input aperture.

6. The diffractive wavefront processor of claim 1, wherein the input optical field has optical field components spanning a plurality of wavelengths and the resulting output optical fields possess respective phase distributions that are individually conjugates of the input optical field components at the plurality of wavelengths.

7. A method of performing optical phase conjugation (OPC) on an input optical field comprising:

providing a diffractive wavefront processor comprising one or more optically transmissive and/or reflective layers arranged in an optical path, each of the one or more optically transmissive and/or reflective substrate layers comprising a plurality of physical features formed on or within the one or more optically transmissive or reflective substrate layers and having different transmission and/or reflection properties as a function of the lateral coordinates across each layer, wherein the one or more optically transmissive and/or reflective substrate layers modulate the input optical field to generate an output optical field with a phase distribution that is the conjugate of the input optical field; and

inputting the input optical field to the diffractive wavefront processor and generating the output optical field with a phase distribution that is the conjugate of the input optical field.

8. The method of claim 7, wherein the conjugated output optical field is reflected back along the optical path and appears at an input aperture.

9. The method of claim 7, wherein the input optical field is in a mm-wave, THz, infrared, visible, or x-ray range of the electromagnetic spectrum.

10. The method of claim 7, wherein the input optical field has a phase profile representing different optical aberrations comprising one or more of coma, astigmatism, spherical aberration, and/or trefoil.

11. The method of claim 7, wherein the input optical field comprises an optical field passing through turbid media, diffuser(s), or scatterer(s).

12. The method of claim 7, wherein the input optical field has optical field components spanning a plurality of wavelengths and the resulting output optical fields possess respective phase distributions that are individually conjugates of the input optical field components at the plurality of wavelengths.

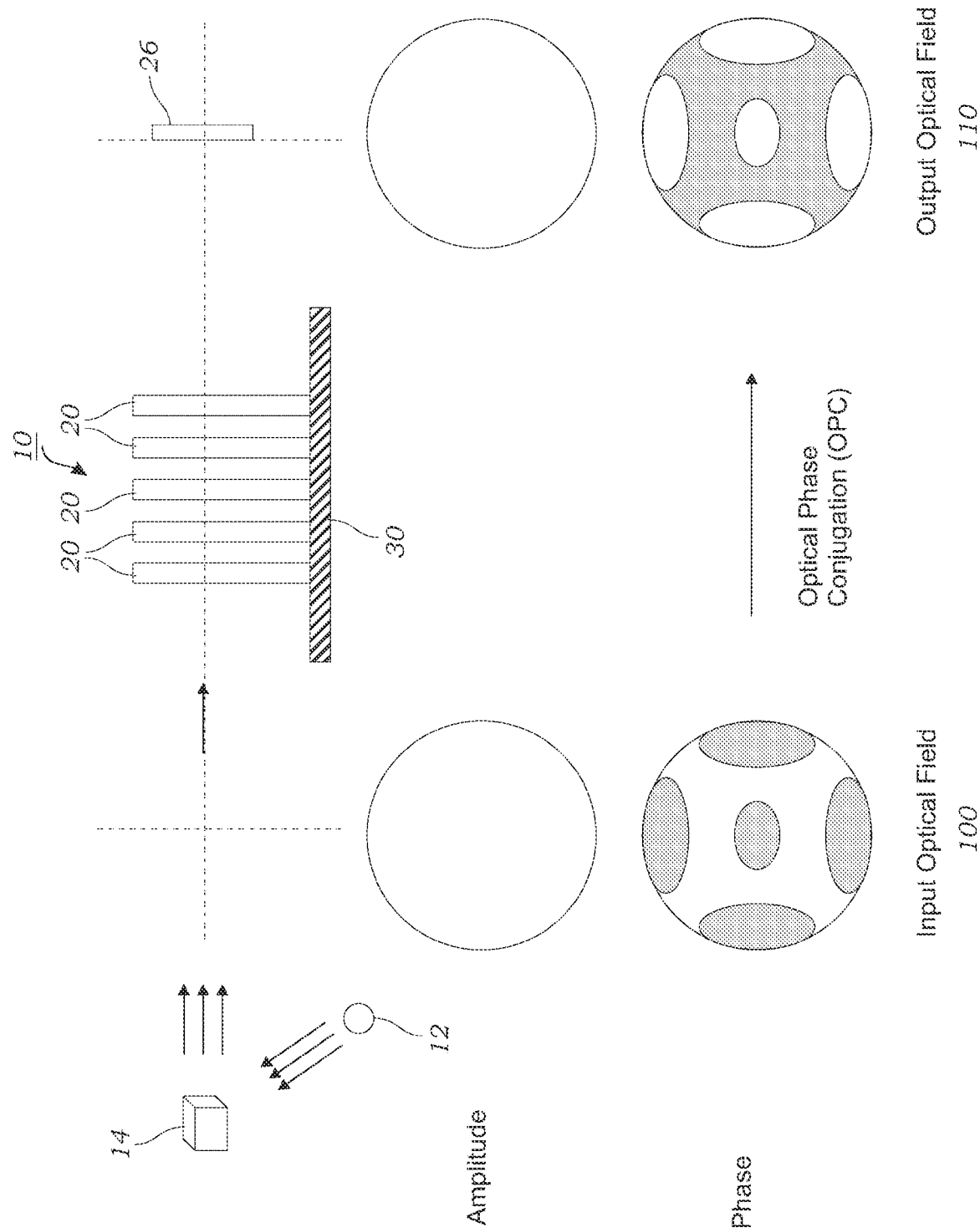


FIG. 1A

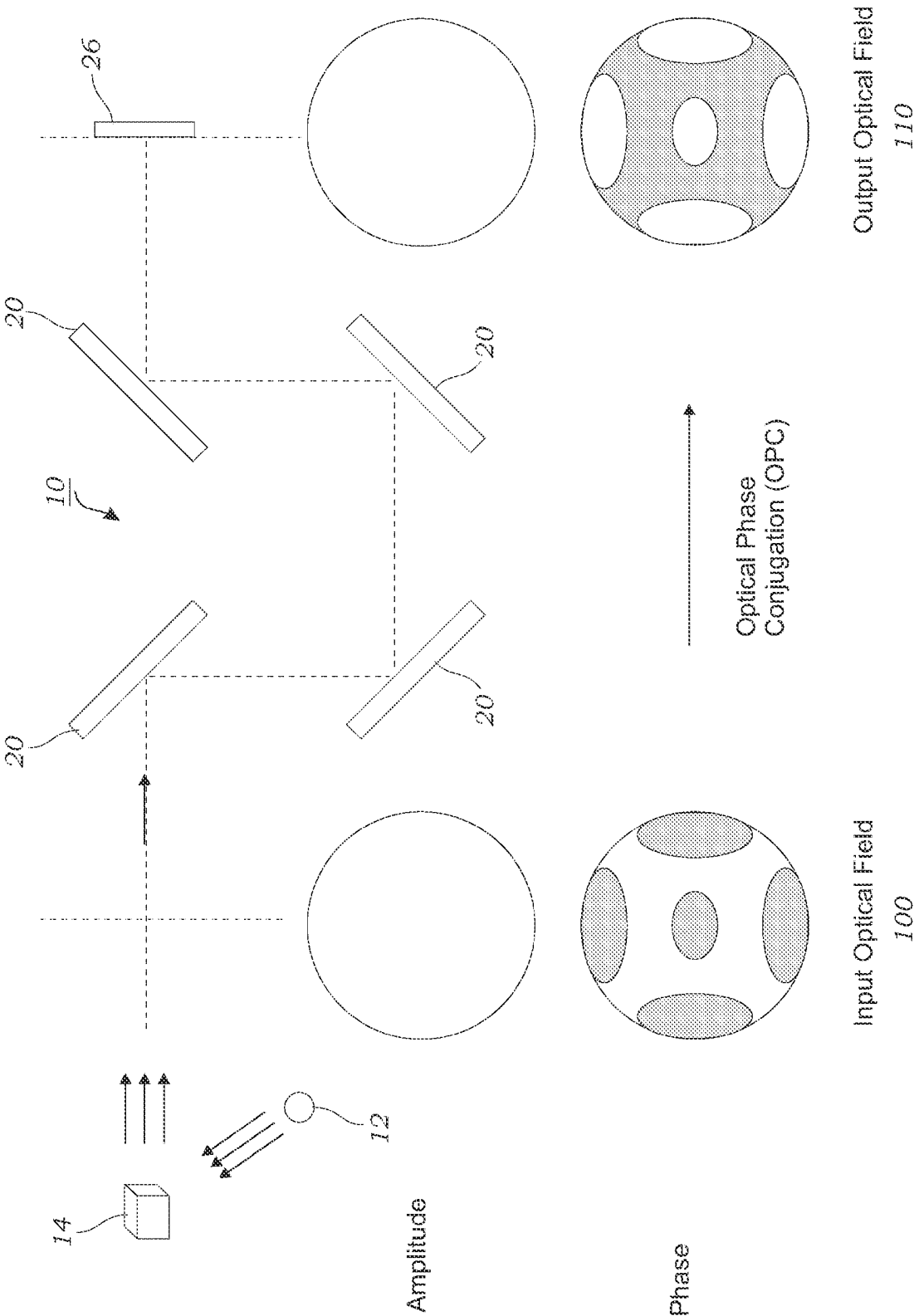


FIG. 1B

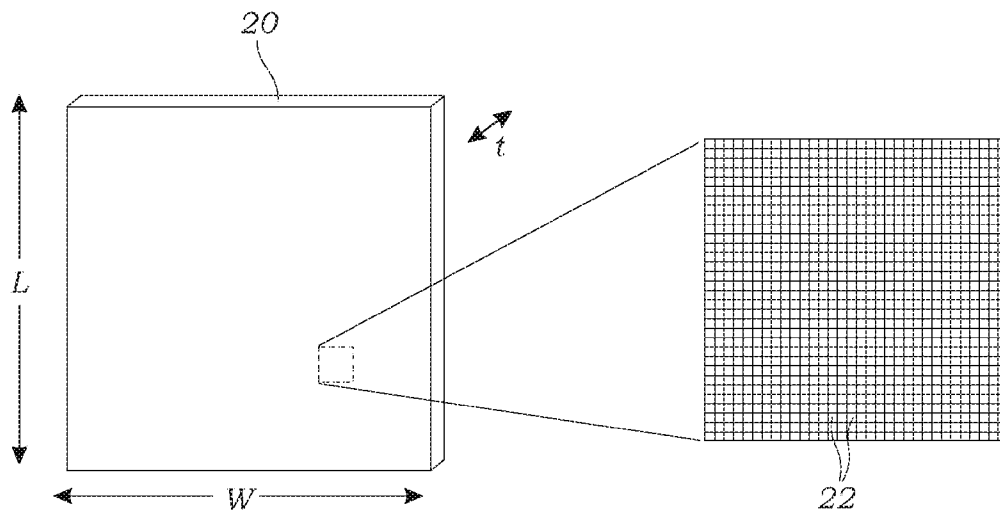


FIG. 2

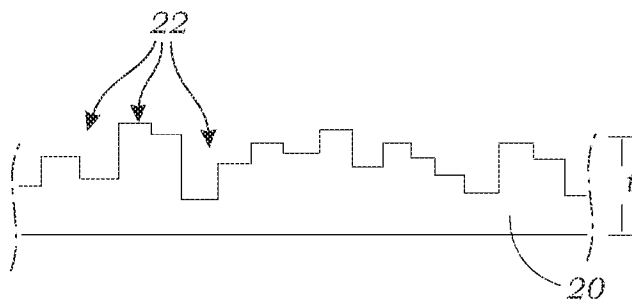


FIG. 3

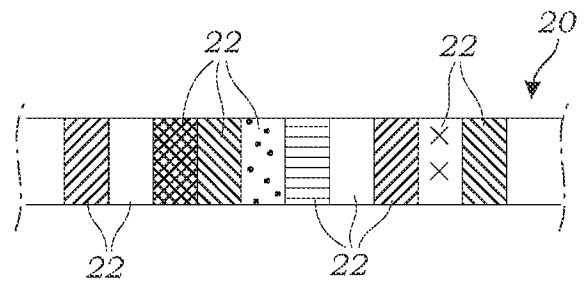


FIG. 4

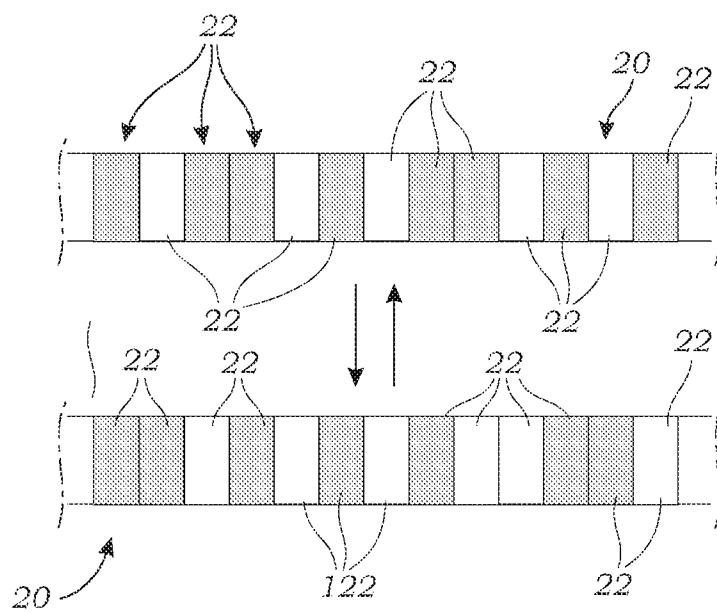


FIG. 5

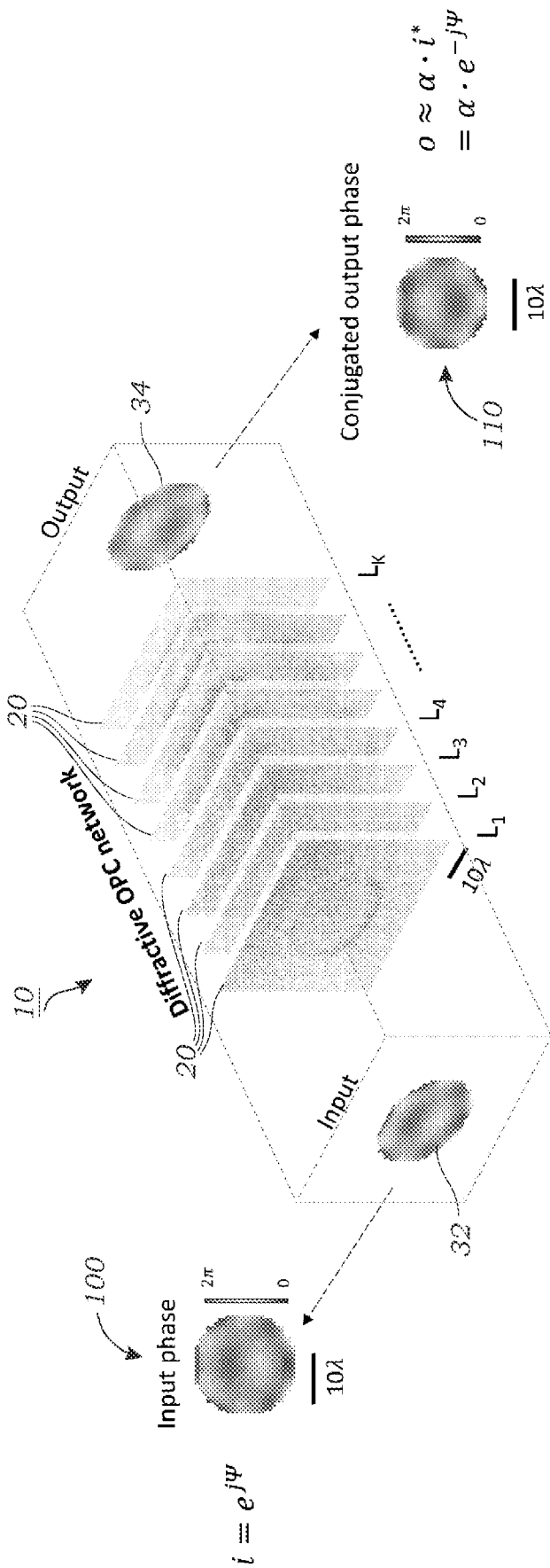


FIG. 6A

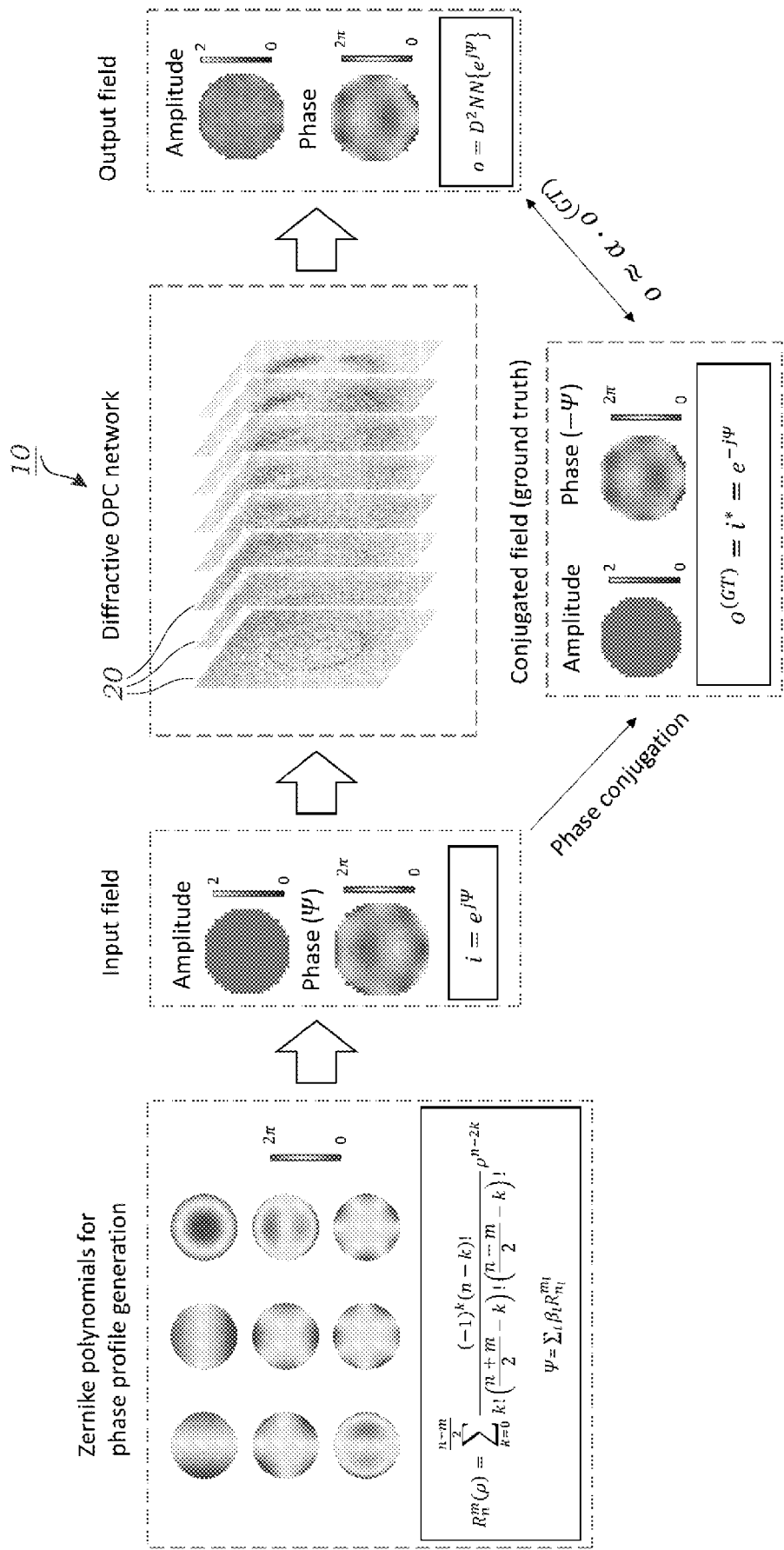


FIG. 6B

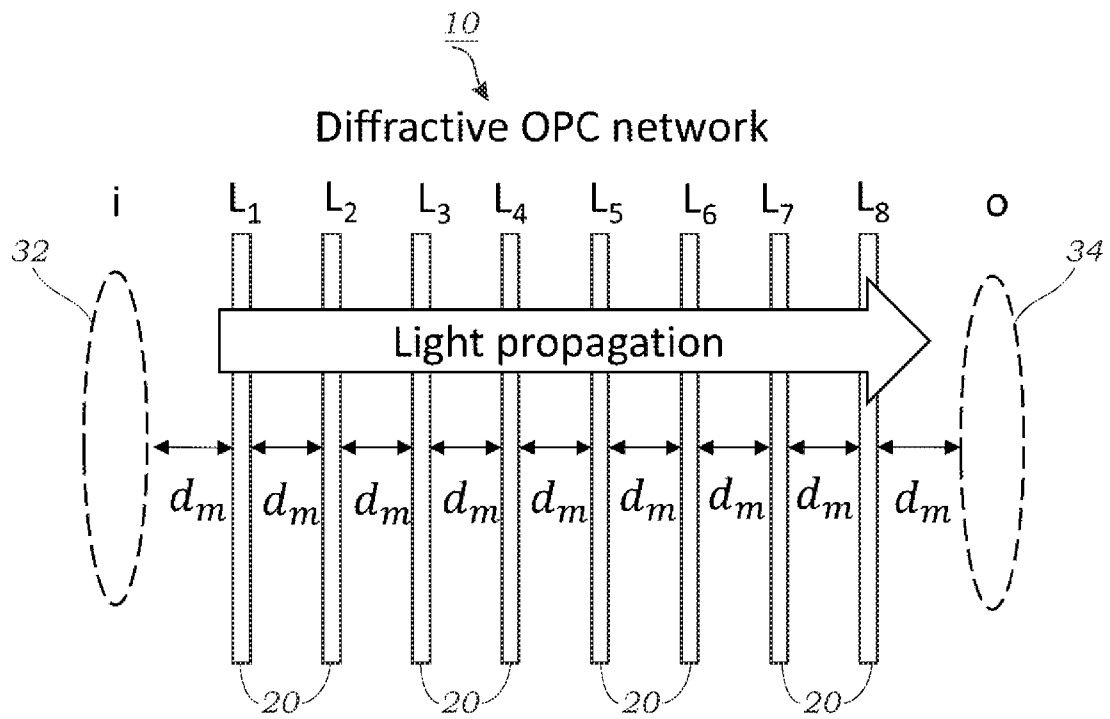


FIG. 7A

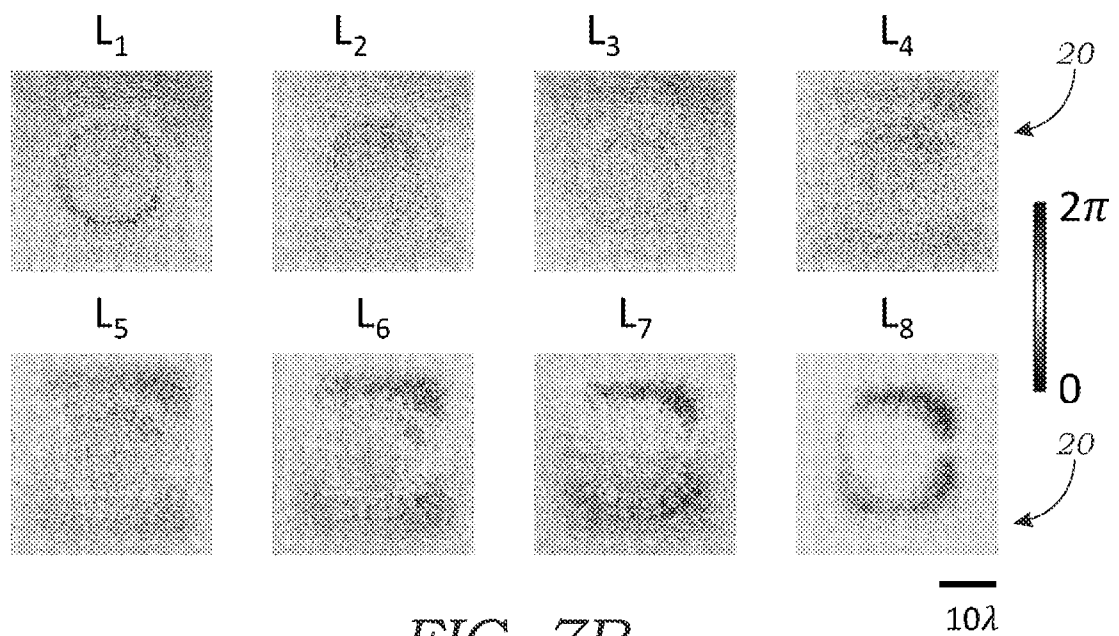


FIG. 7B

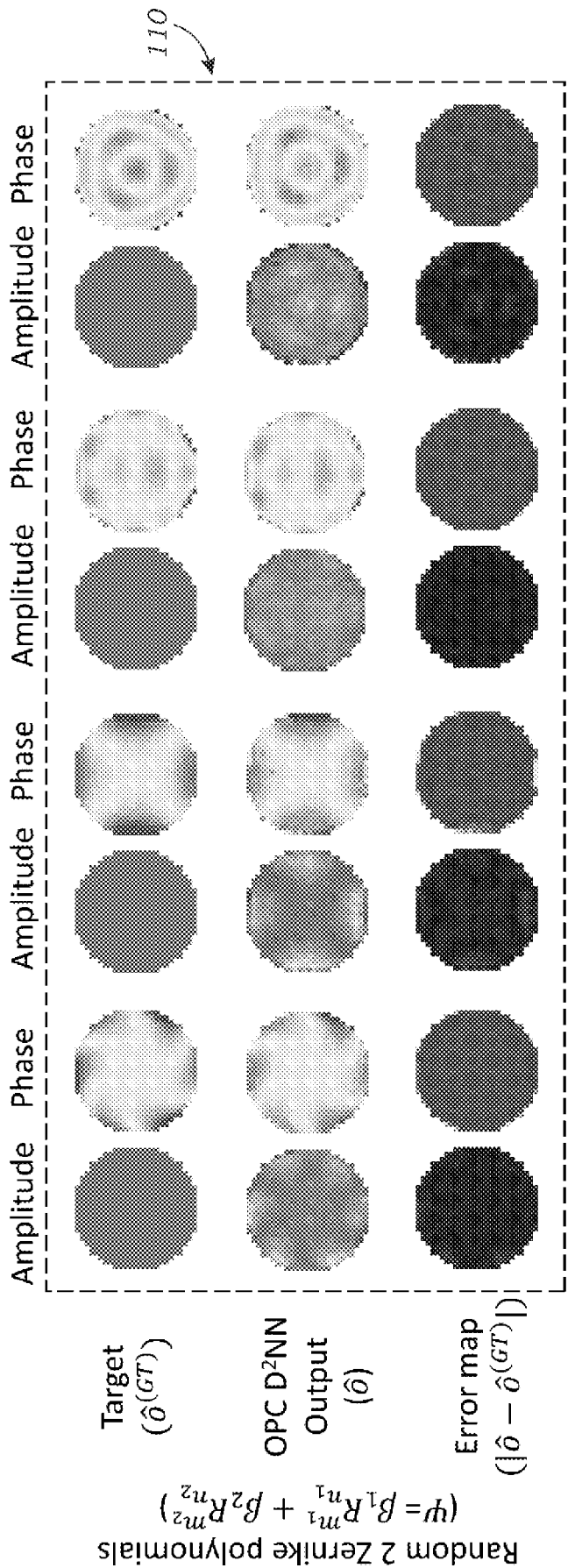


FIG. 7C

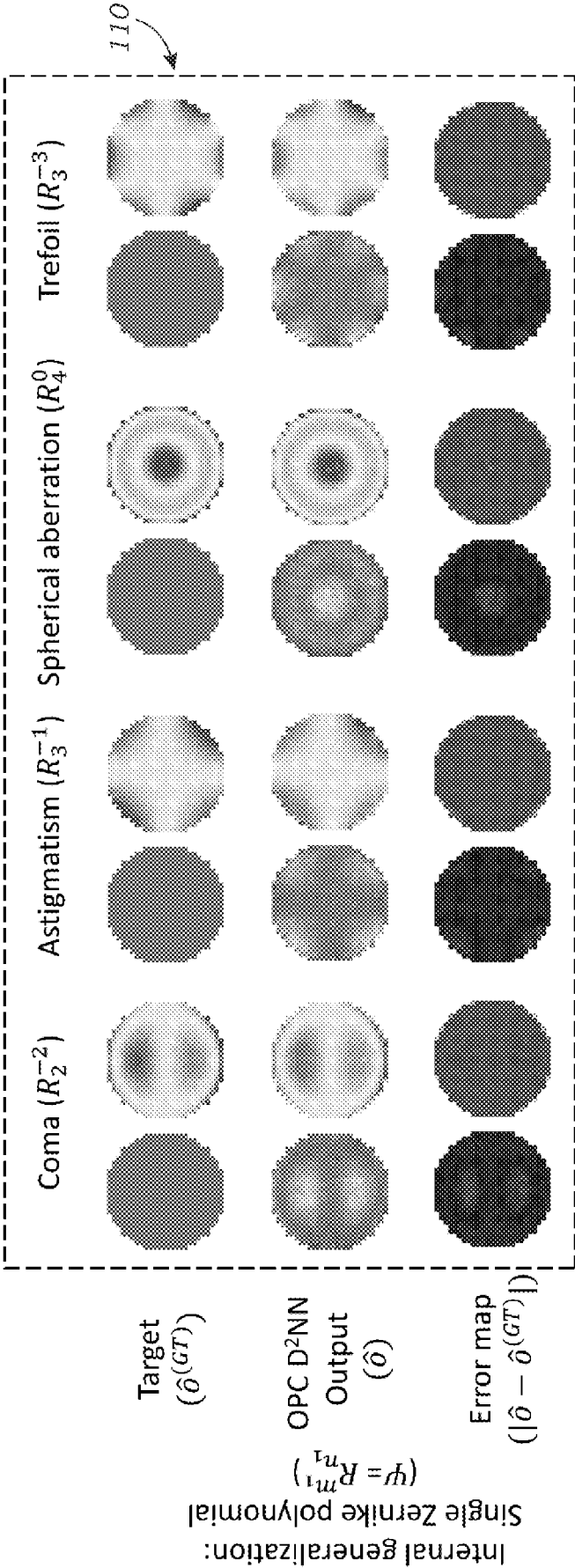


FIG. 7D

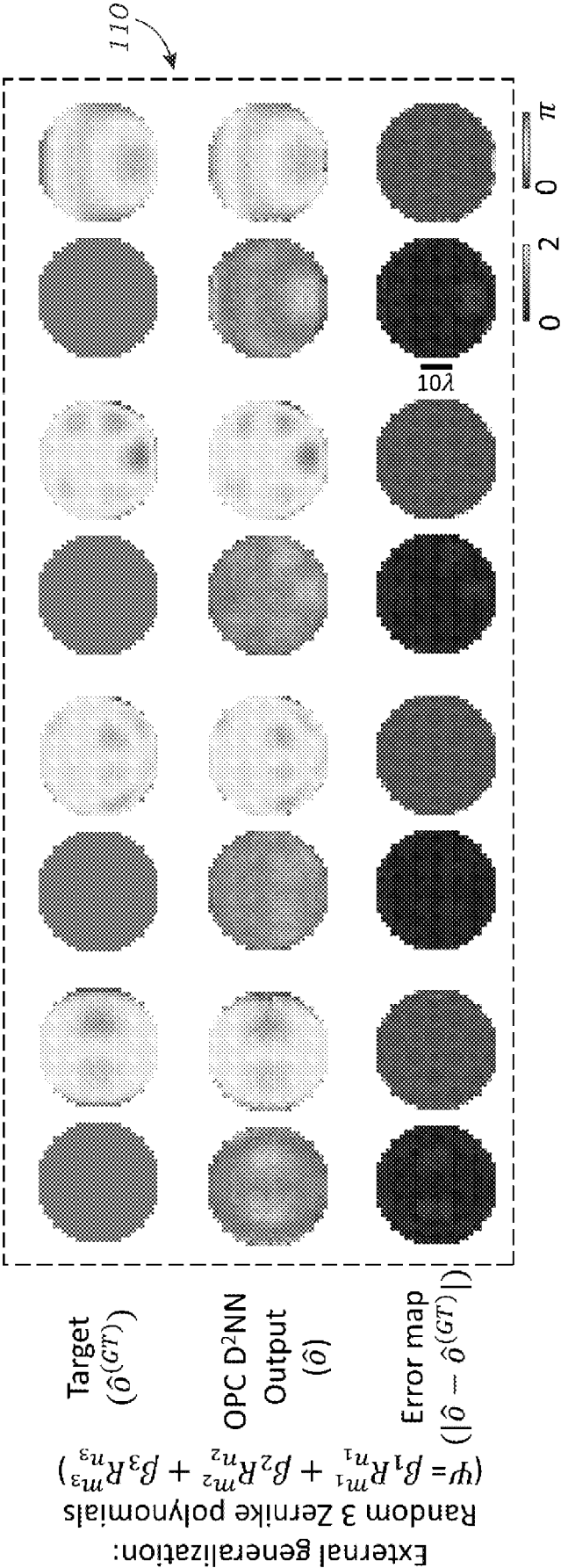


FIG. 7E

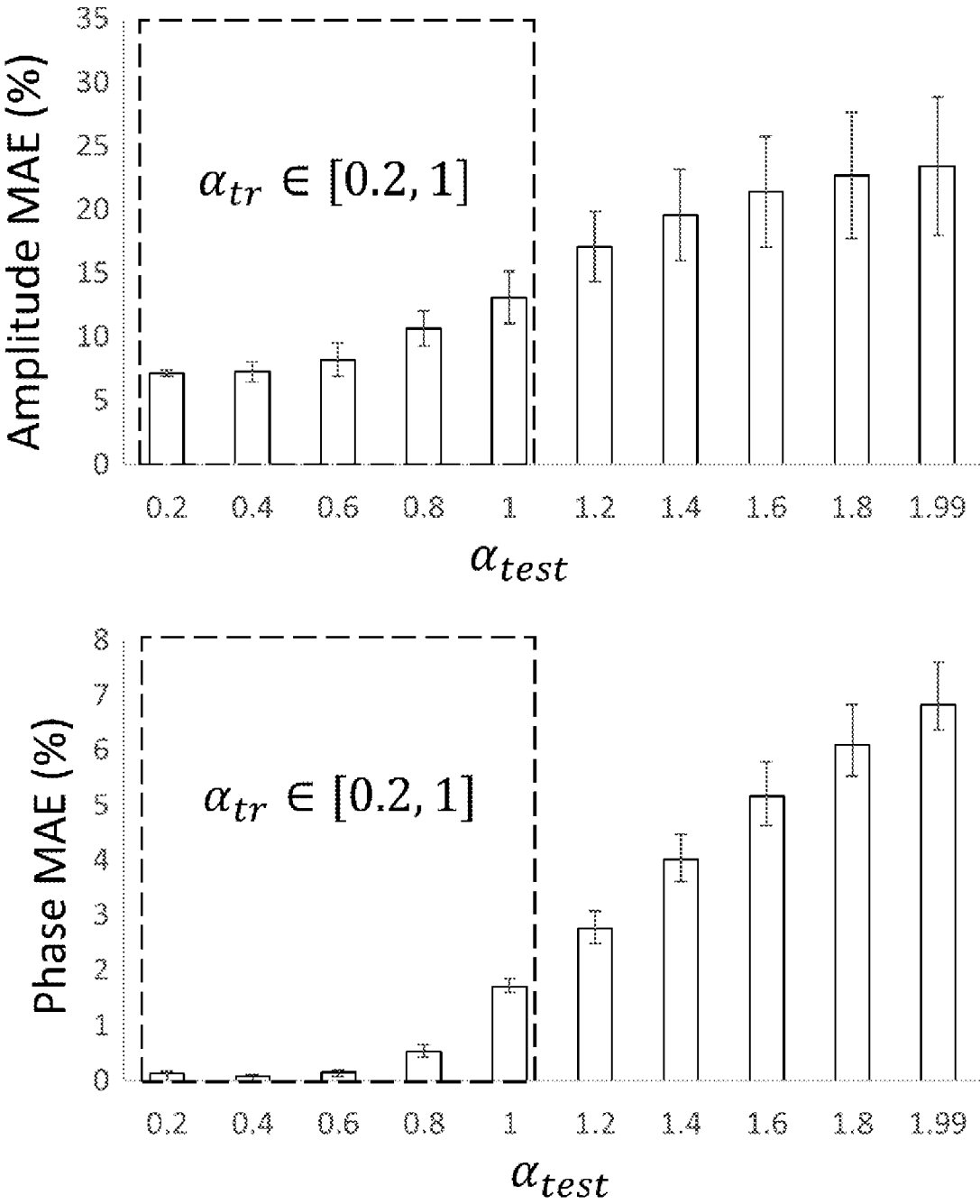
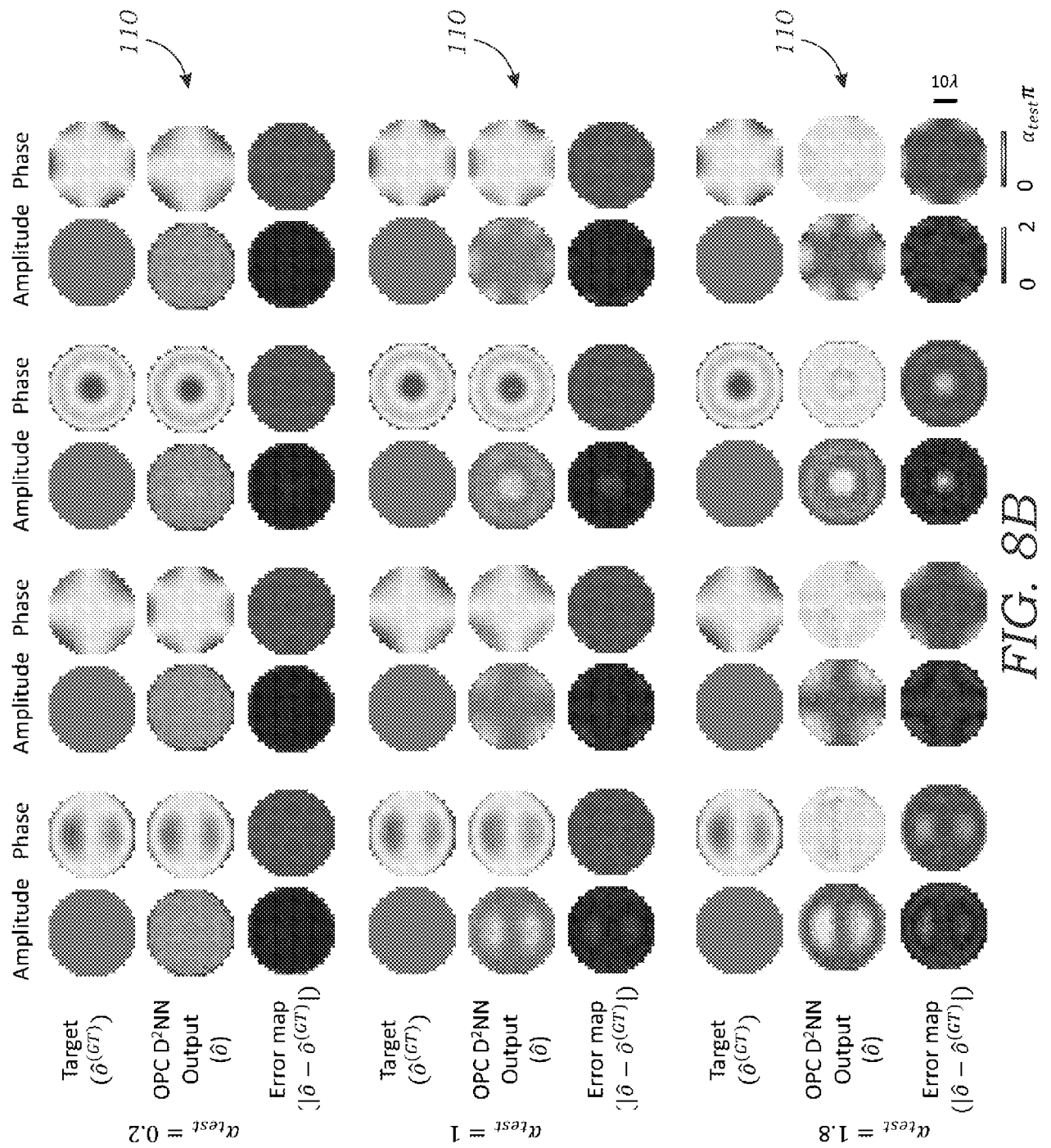


FIG. 8A



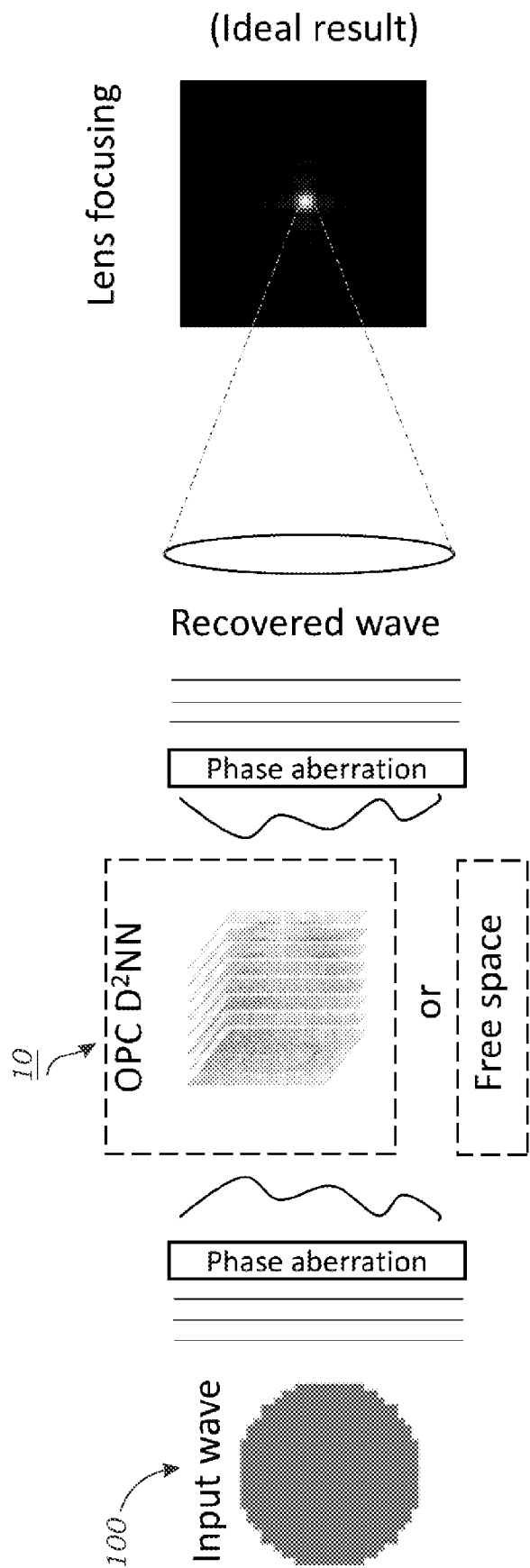
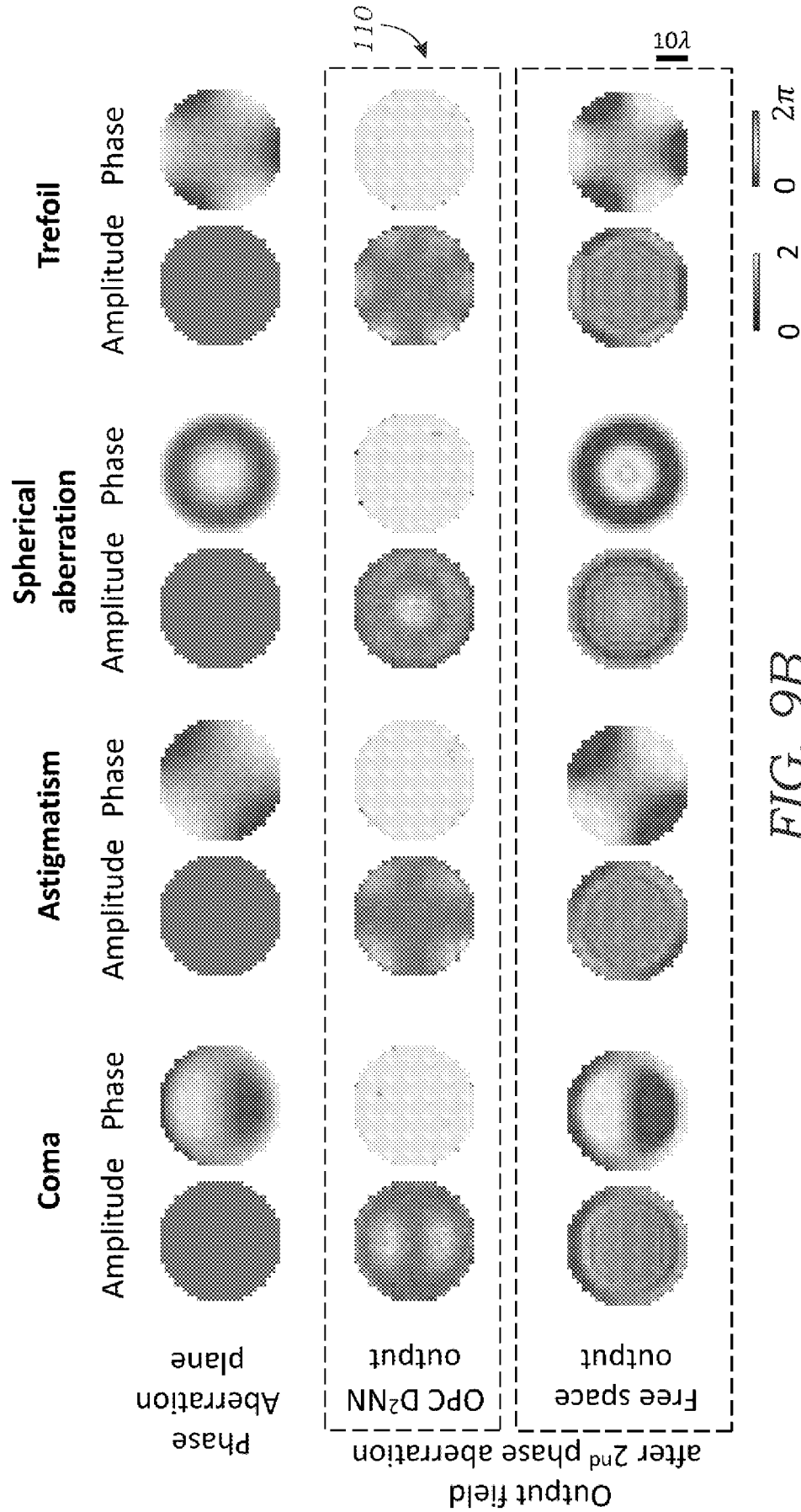
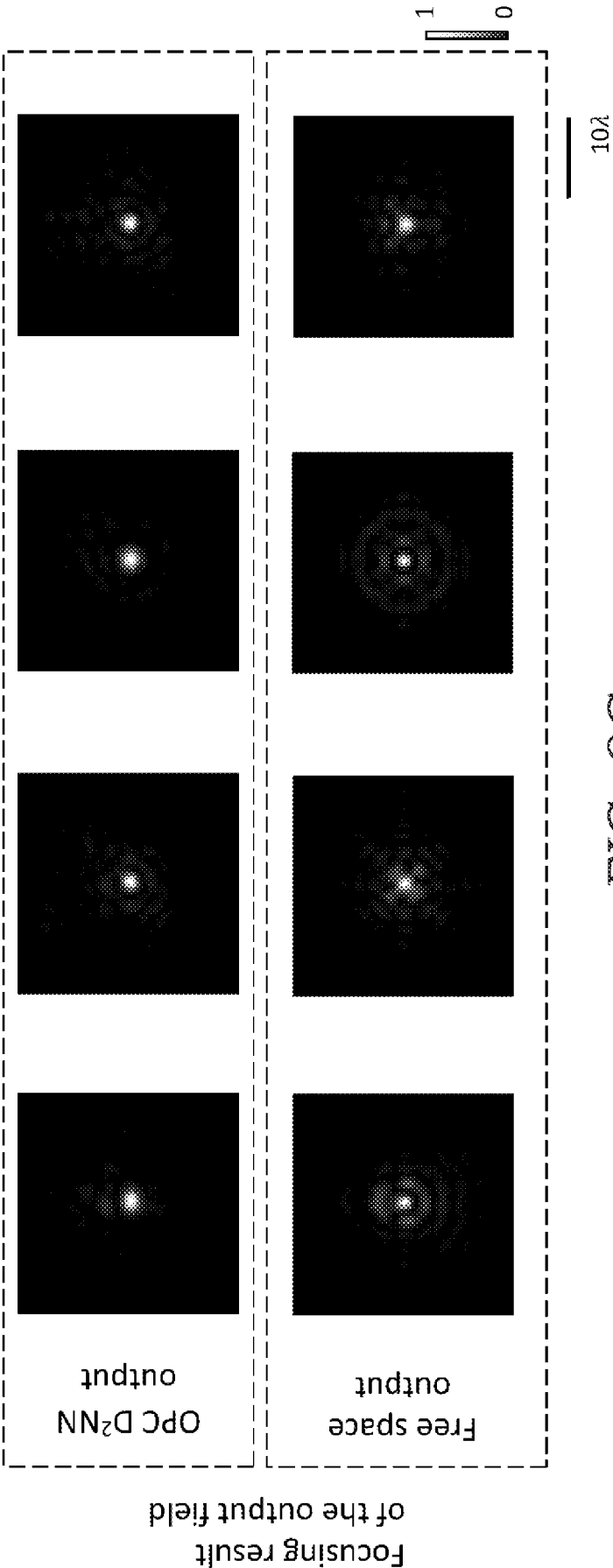
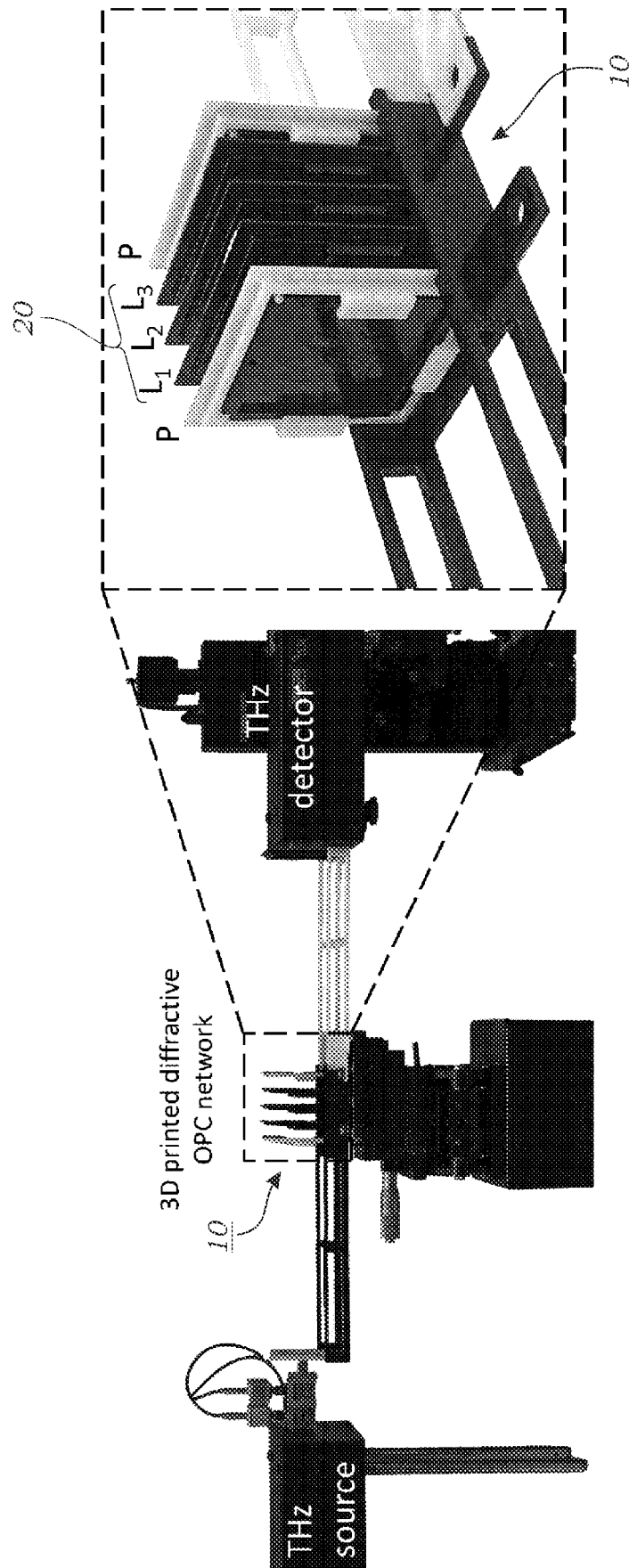
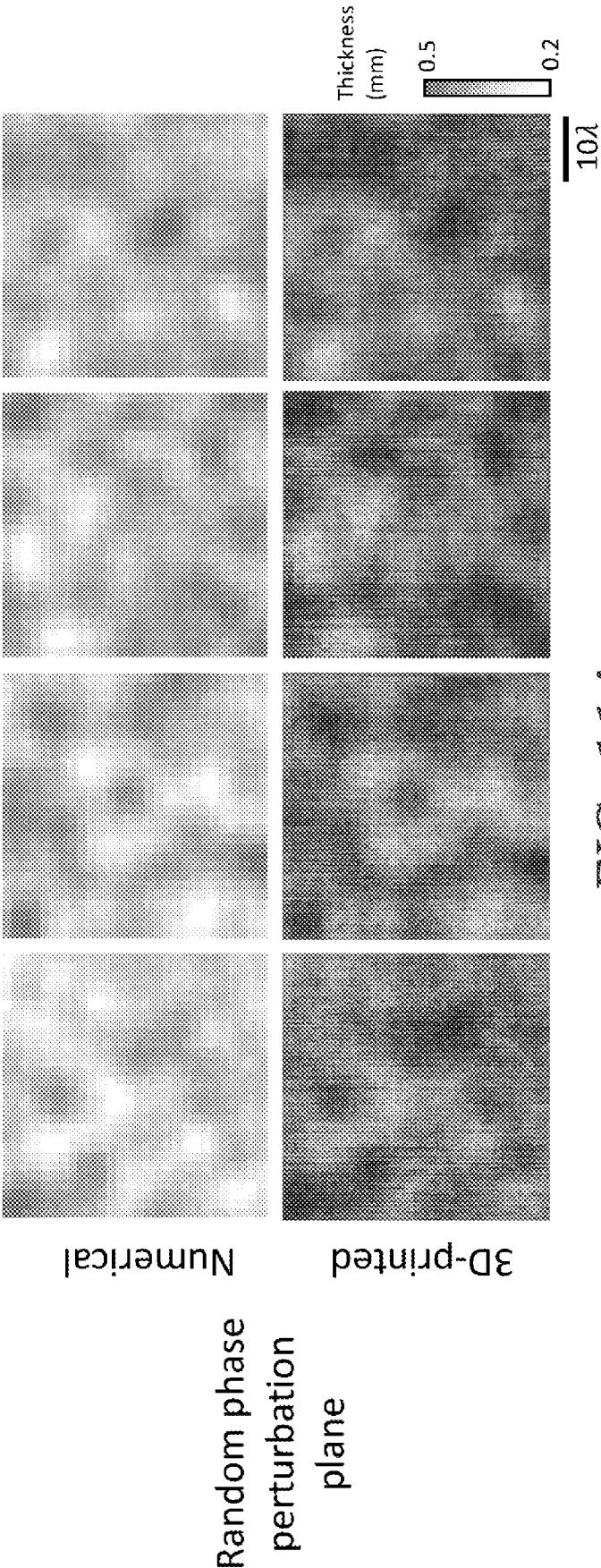


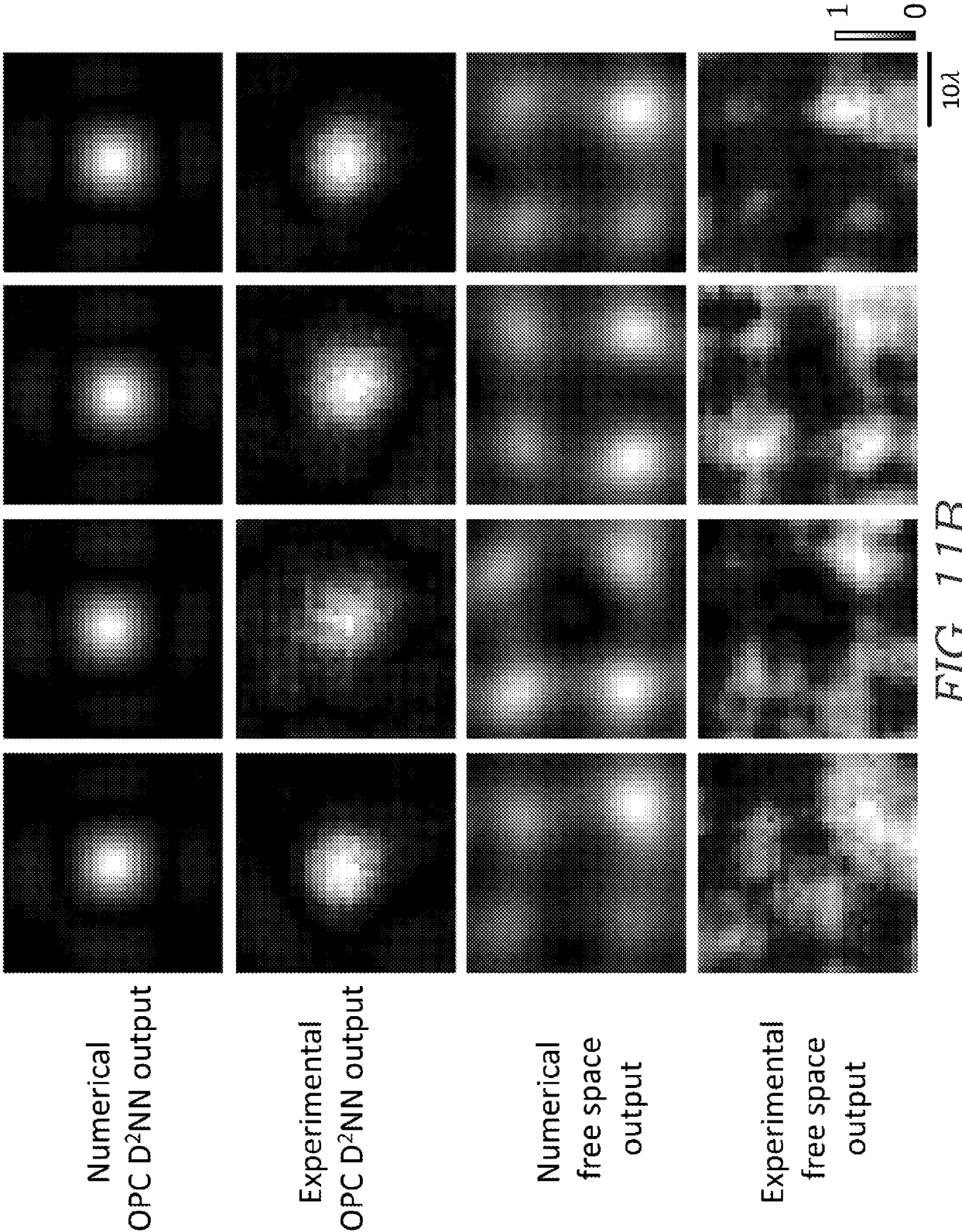
FIG. 9A











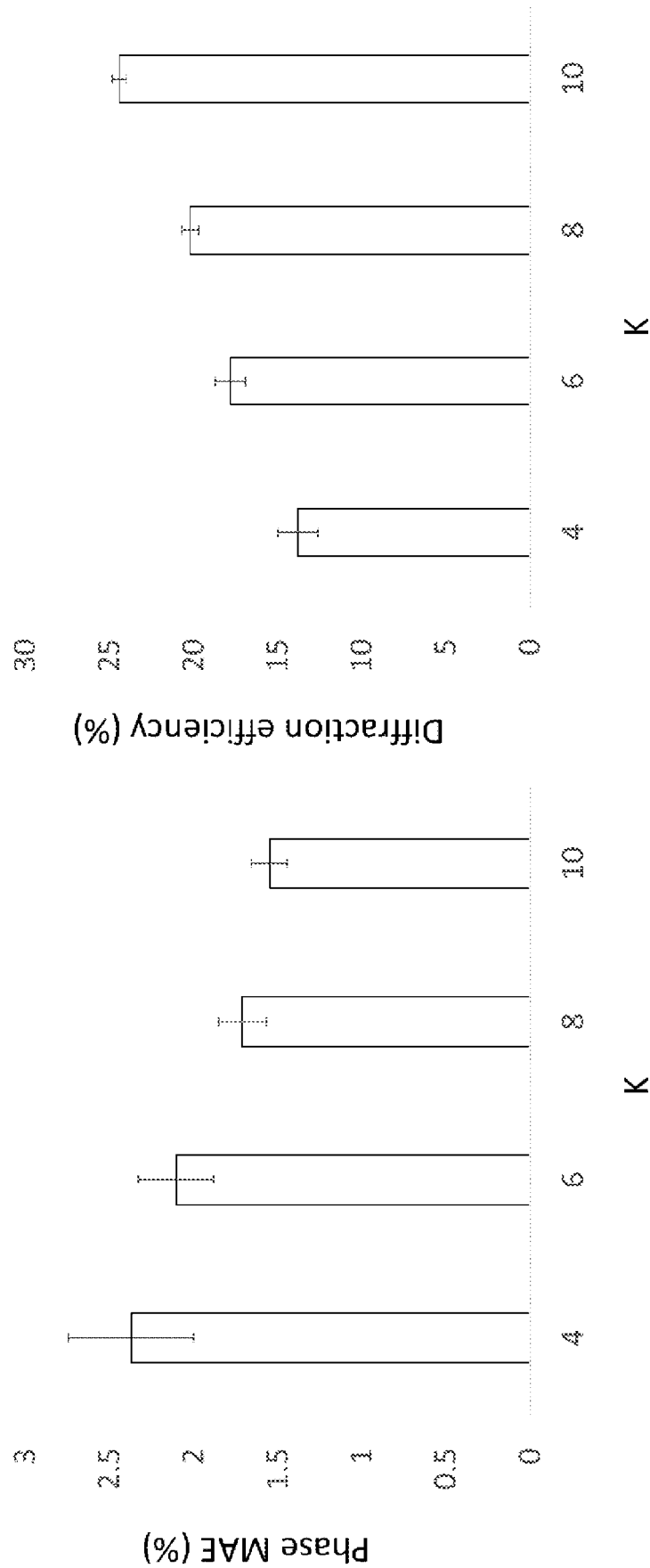


FIG. 12A

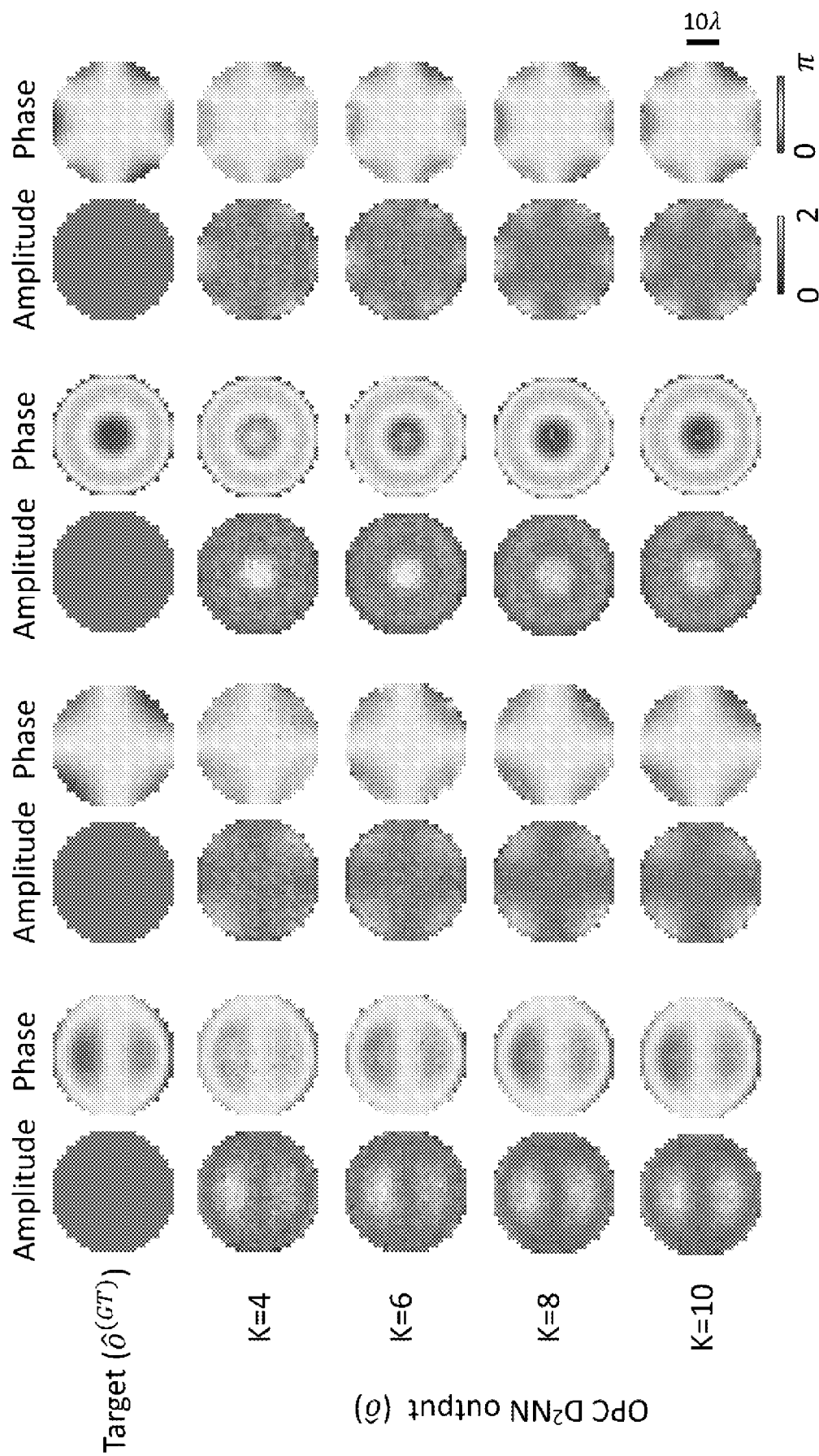


FIG. 12B

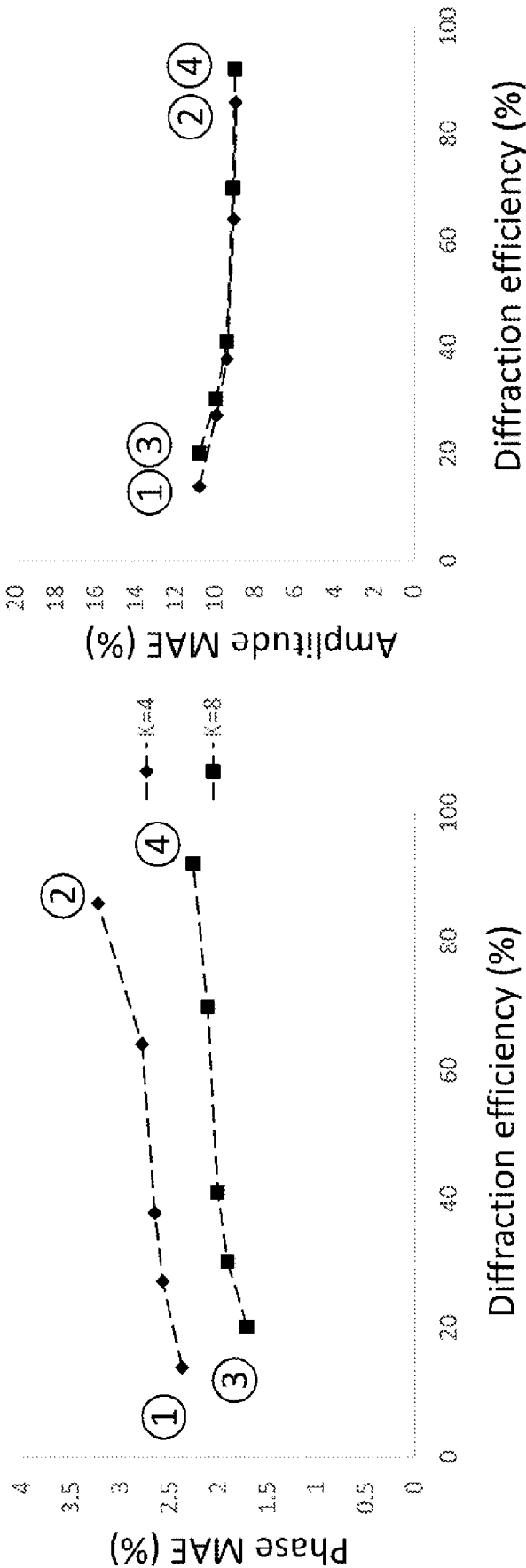


FIG. 13A

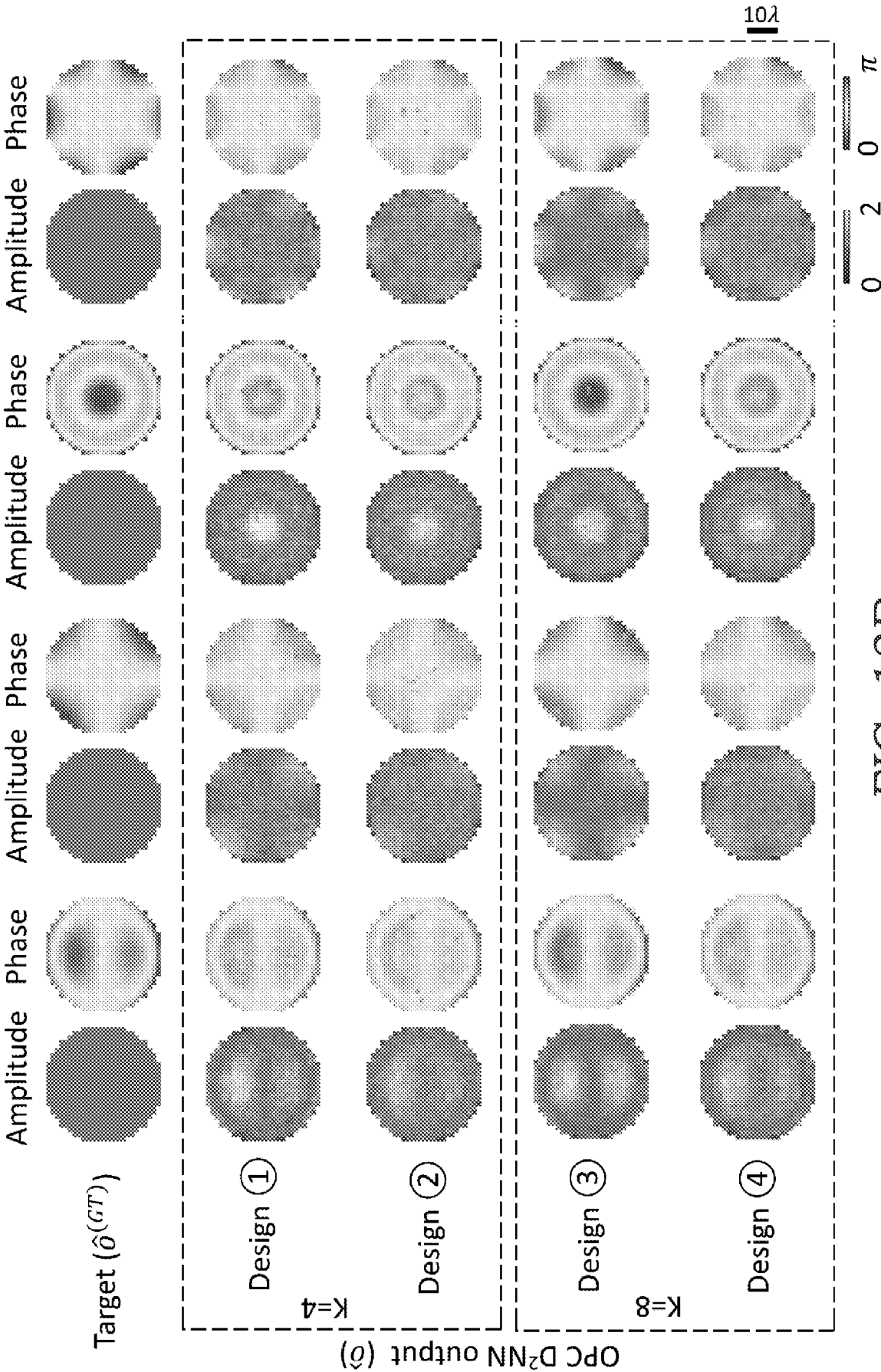
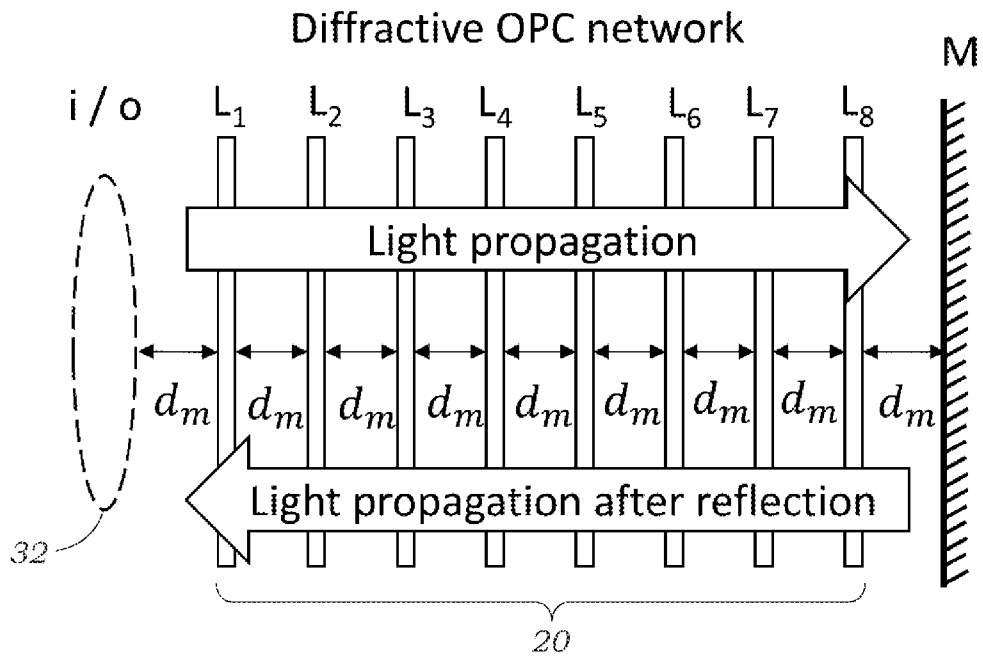
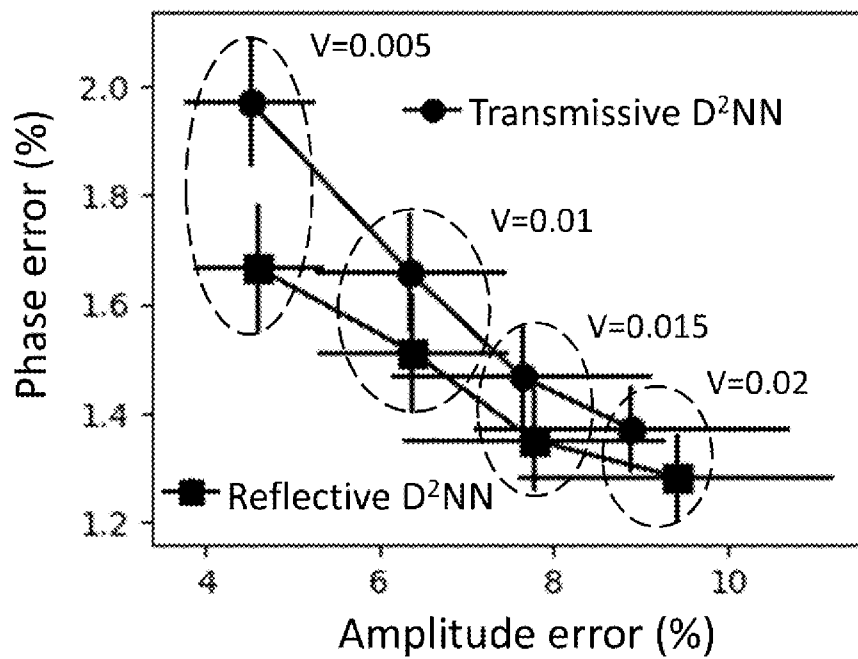


FIG. 13B

*FIG. 14A**FIG. 14B*

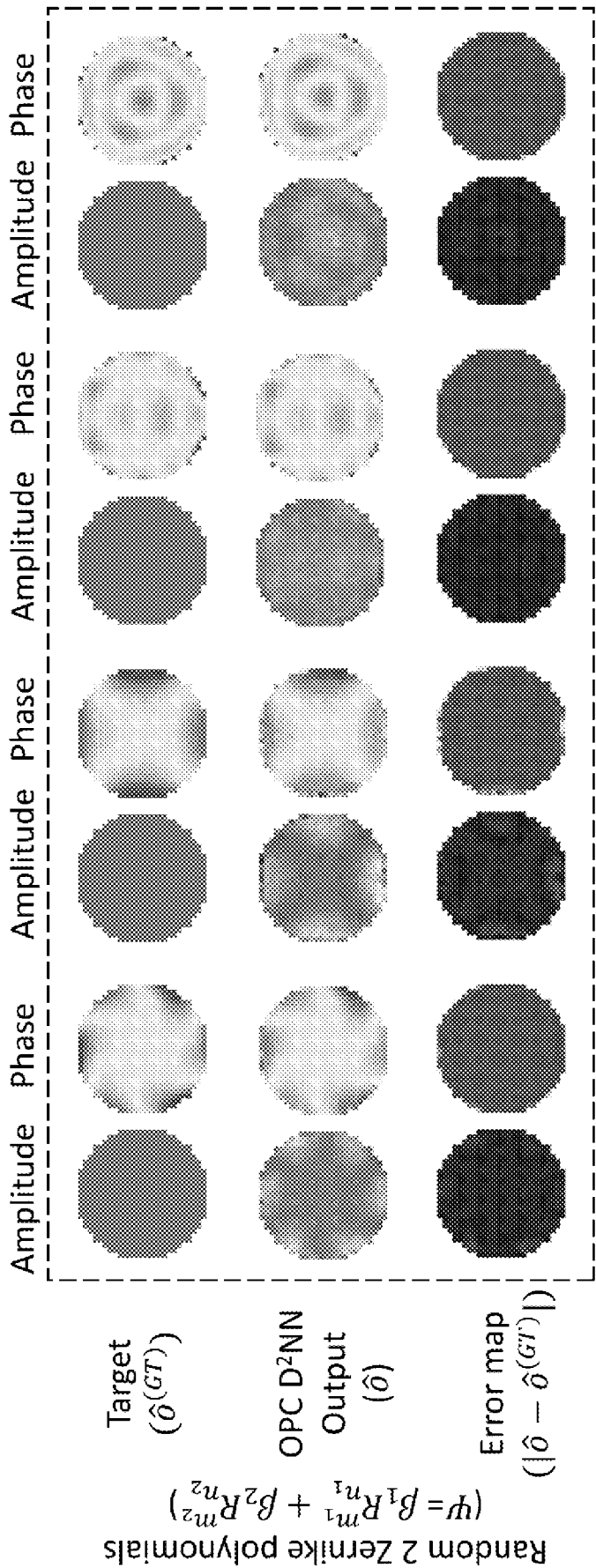


FIG. 14C

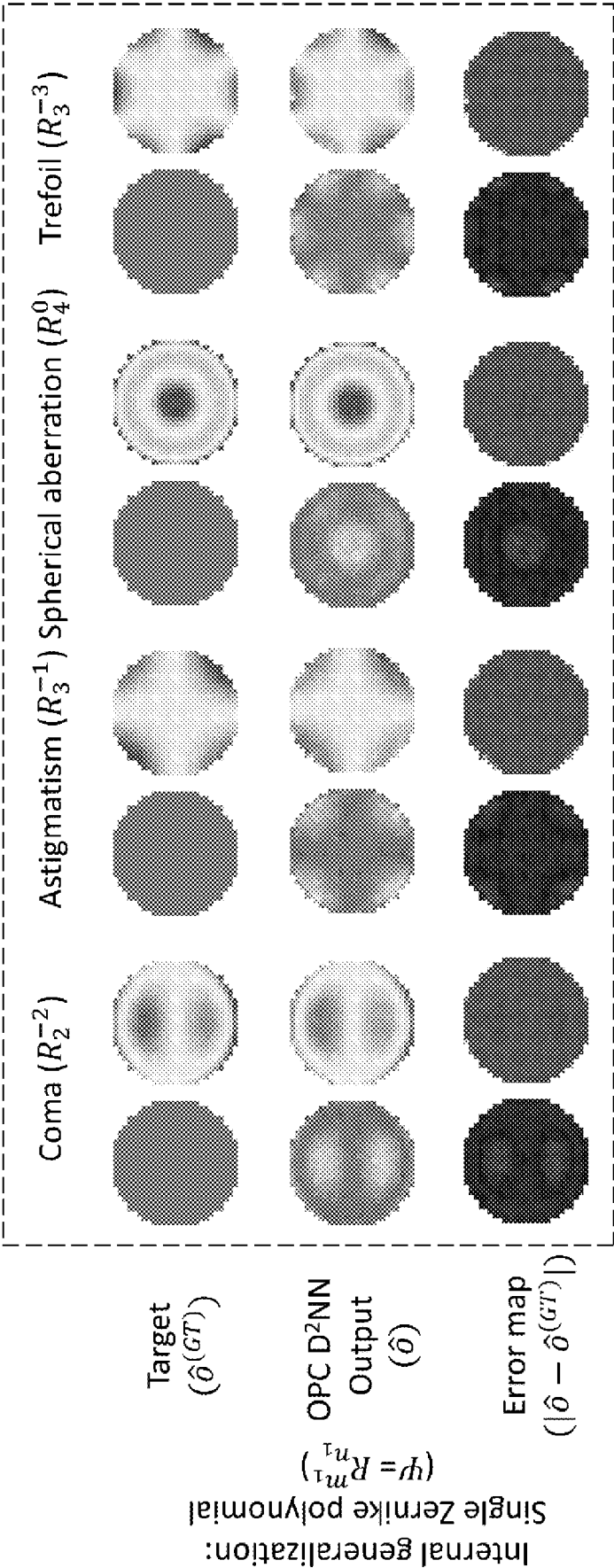


FIG. 14D

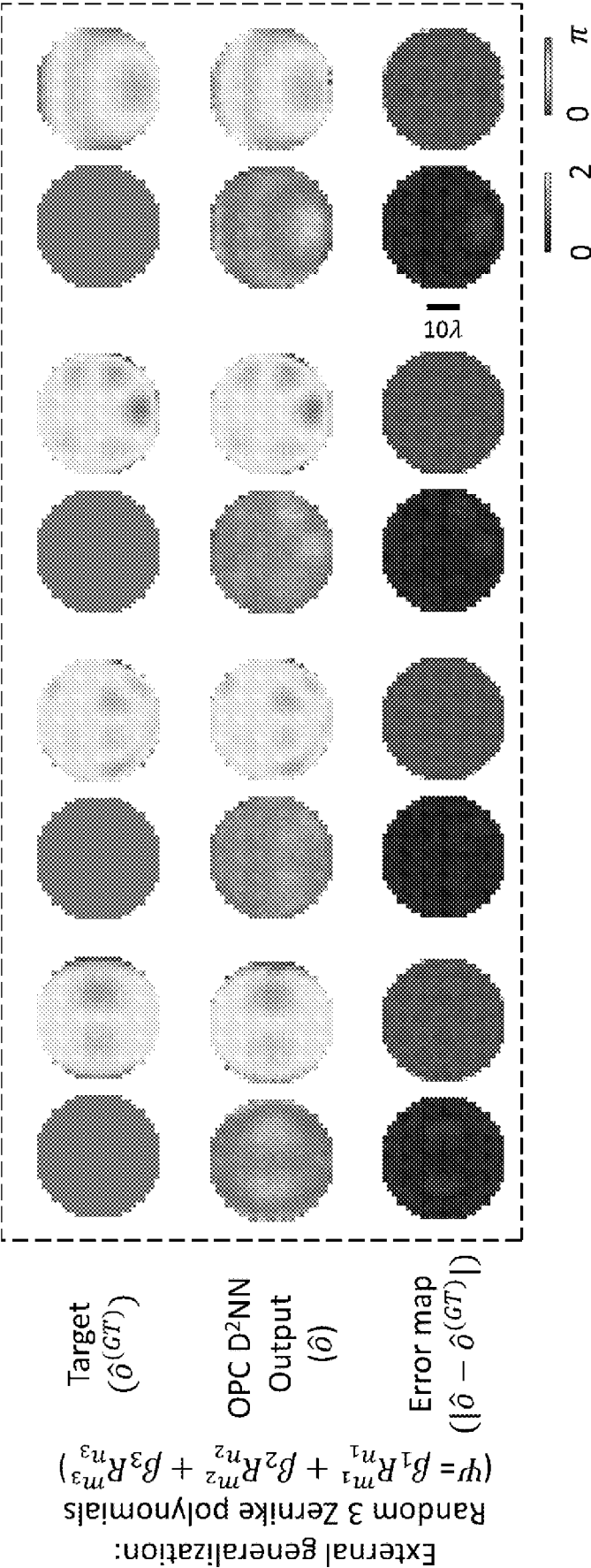


FIG. 14E

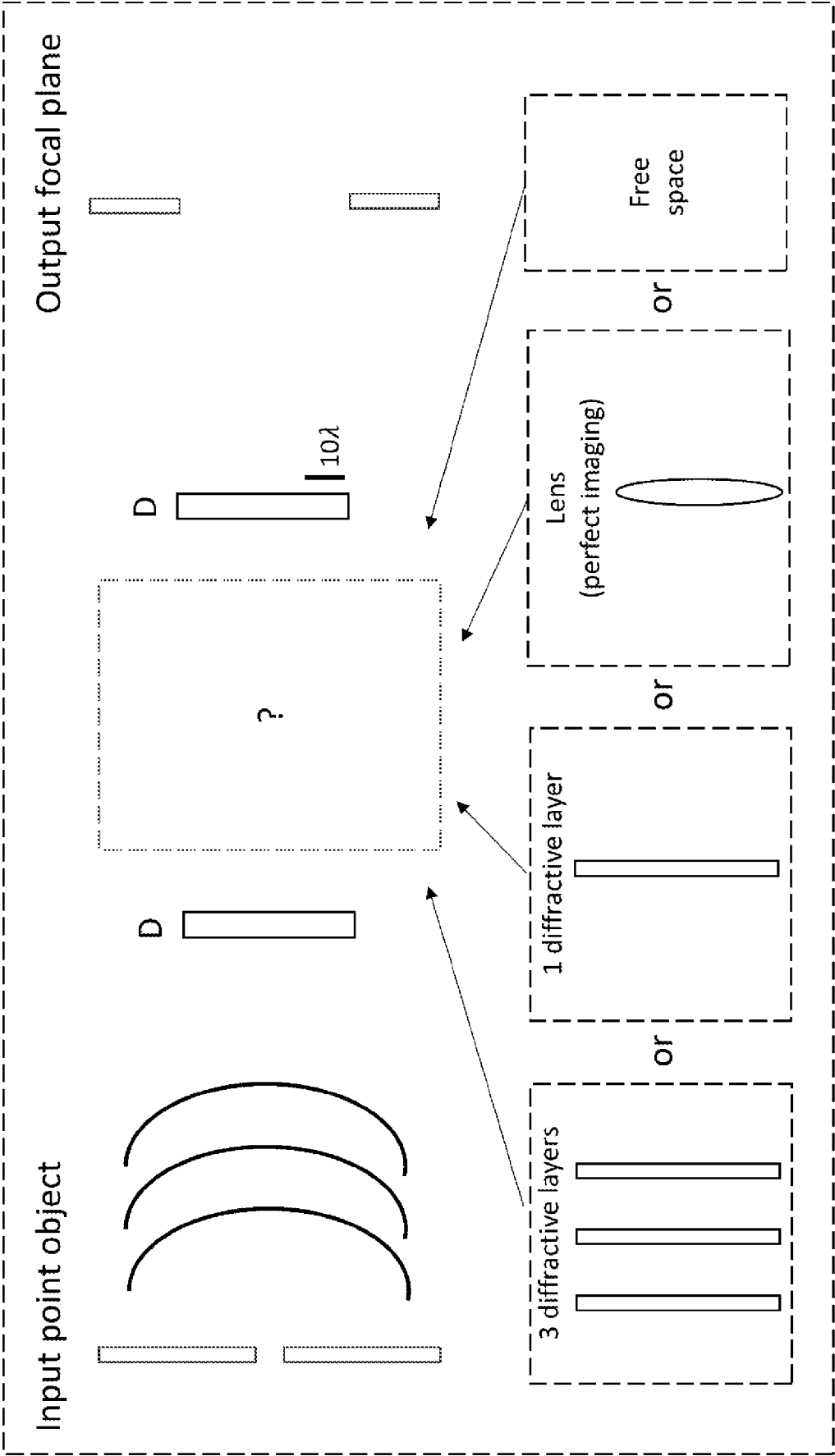


FIG. 15A

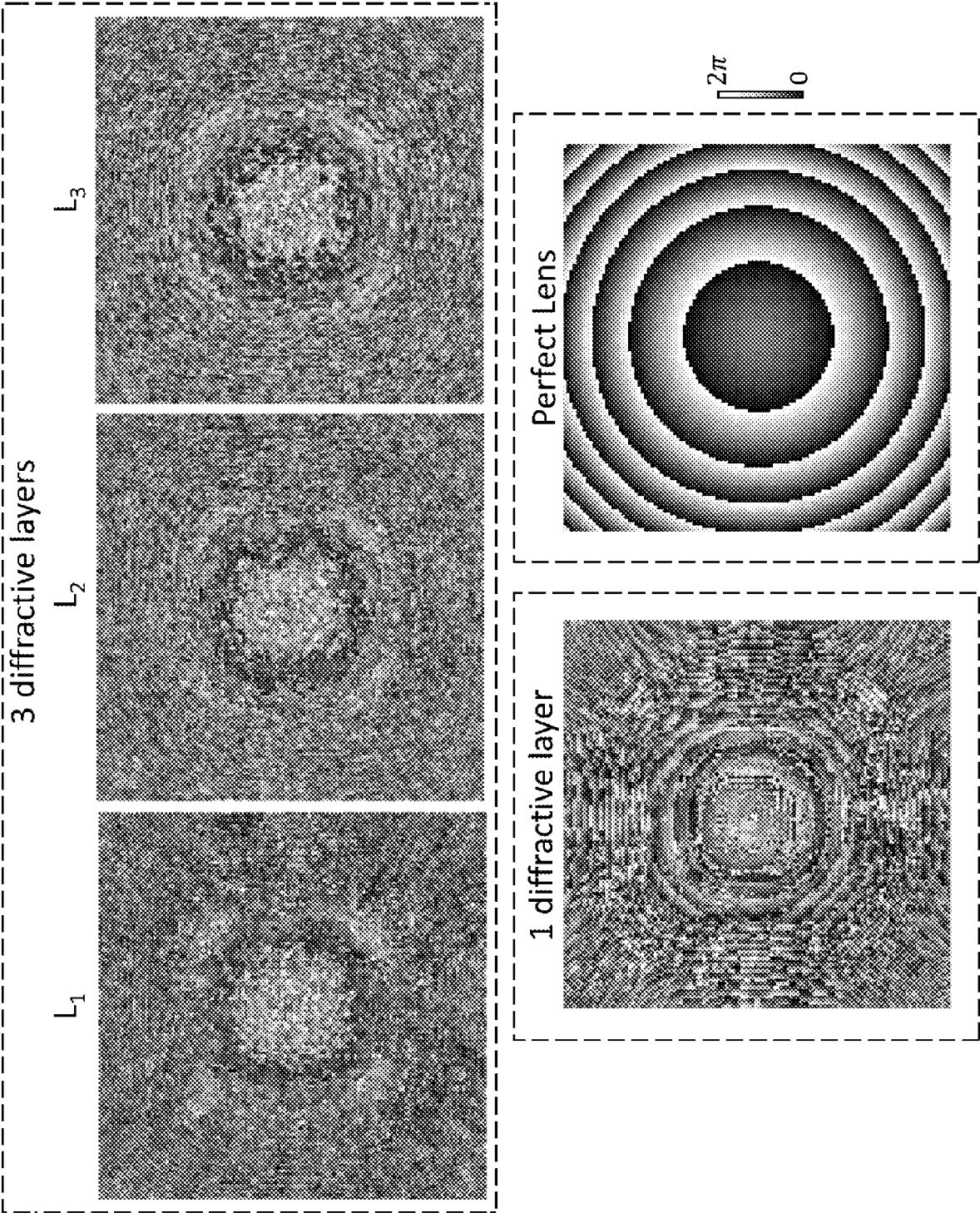
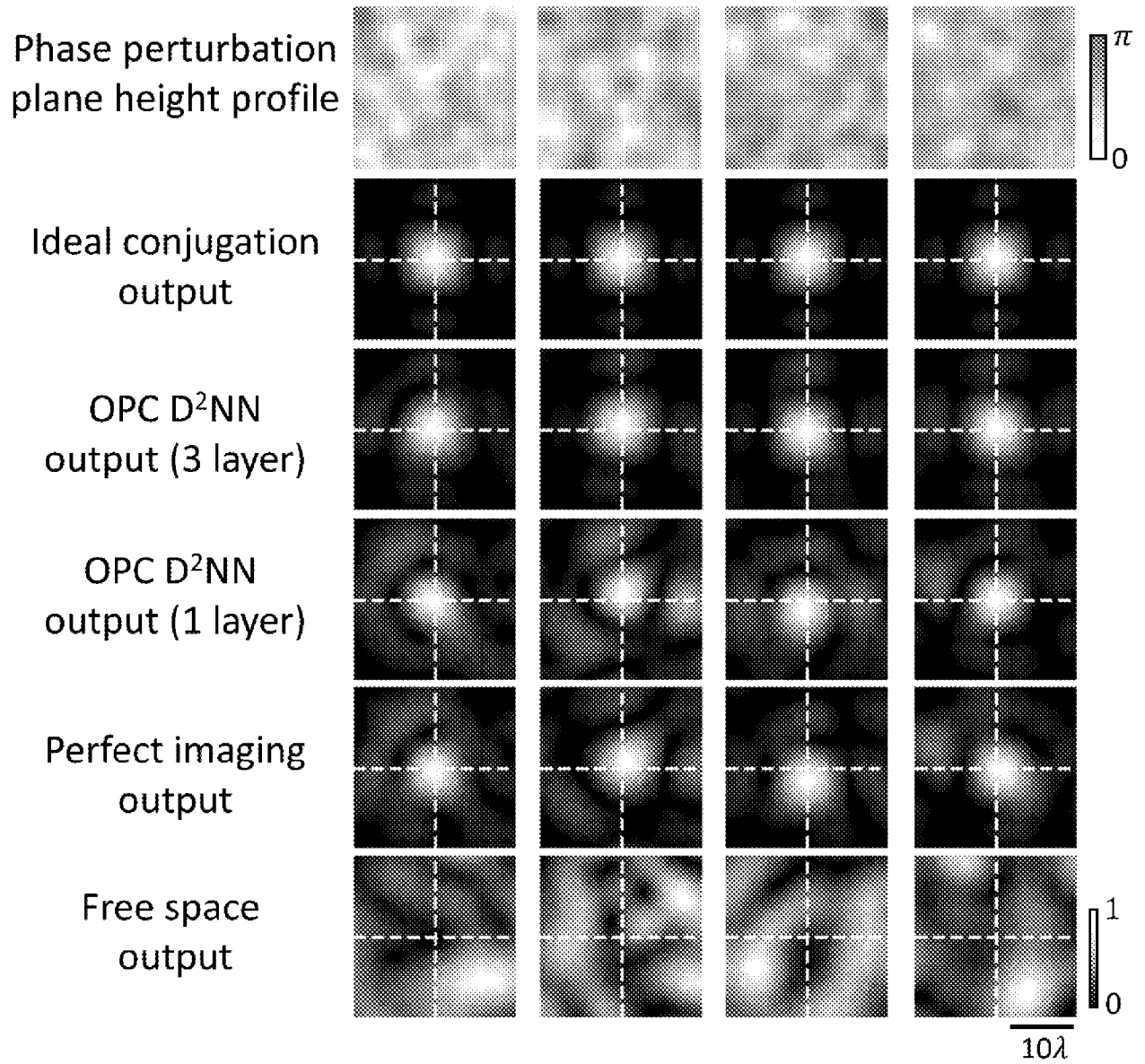


FIG. 15B

*FIG. 16*

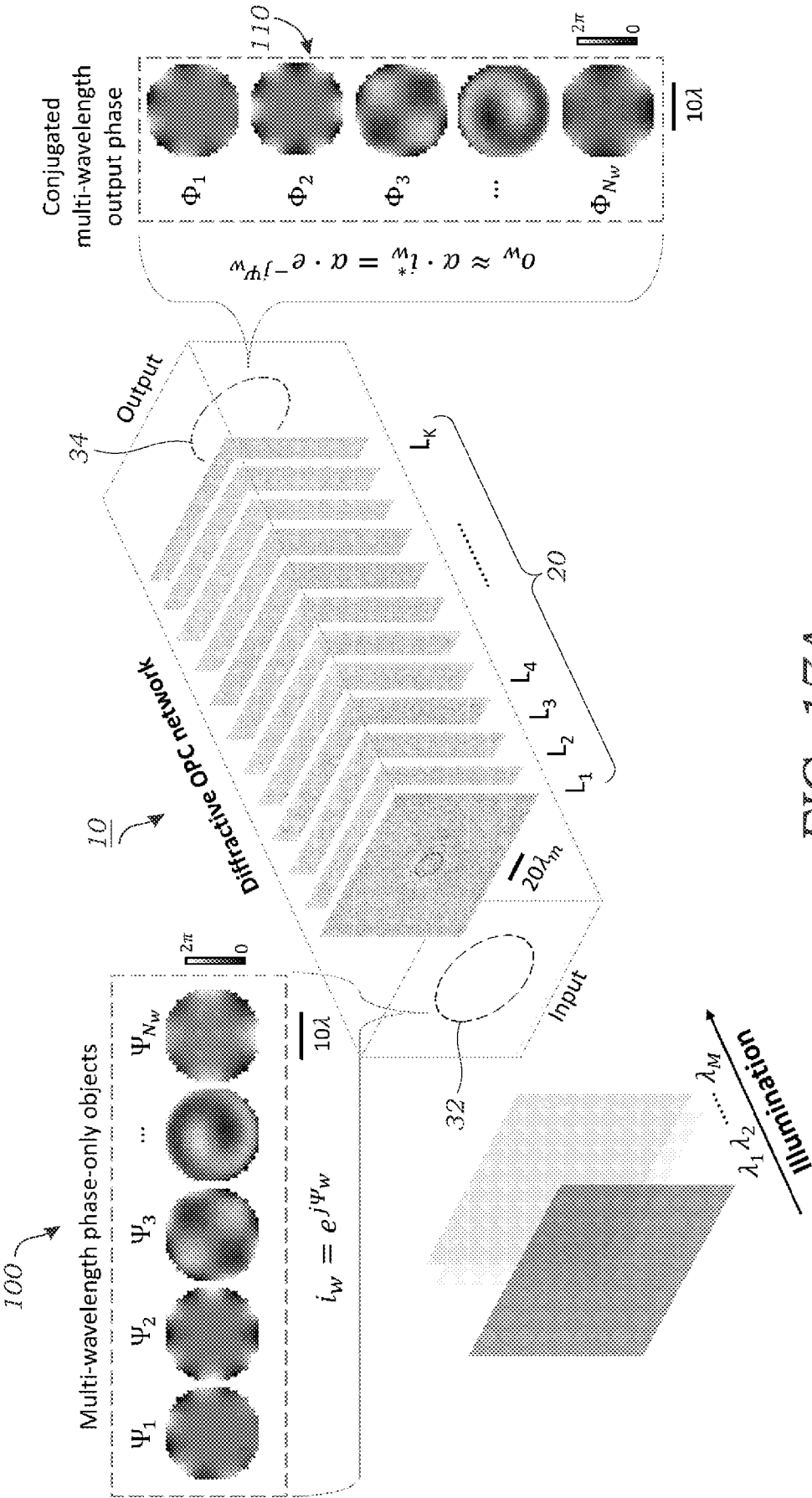


FIG. 17A

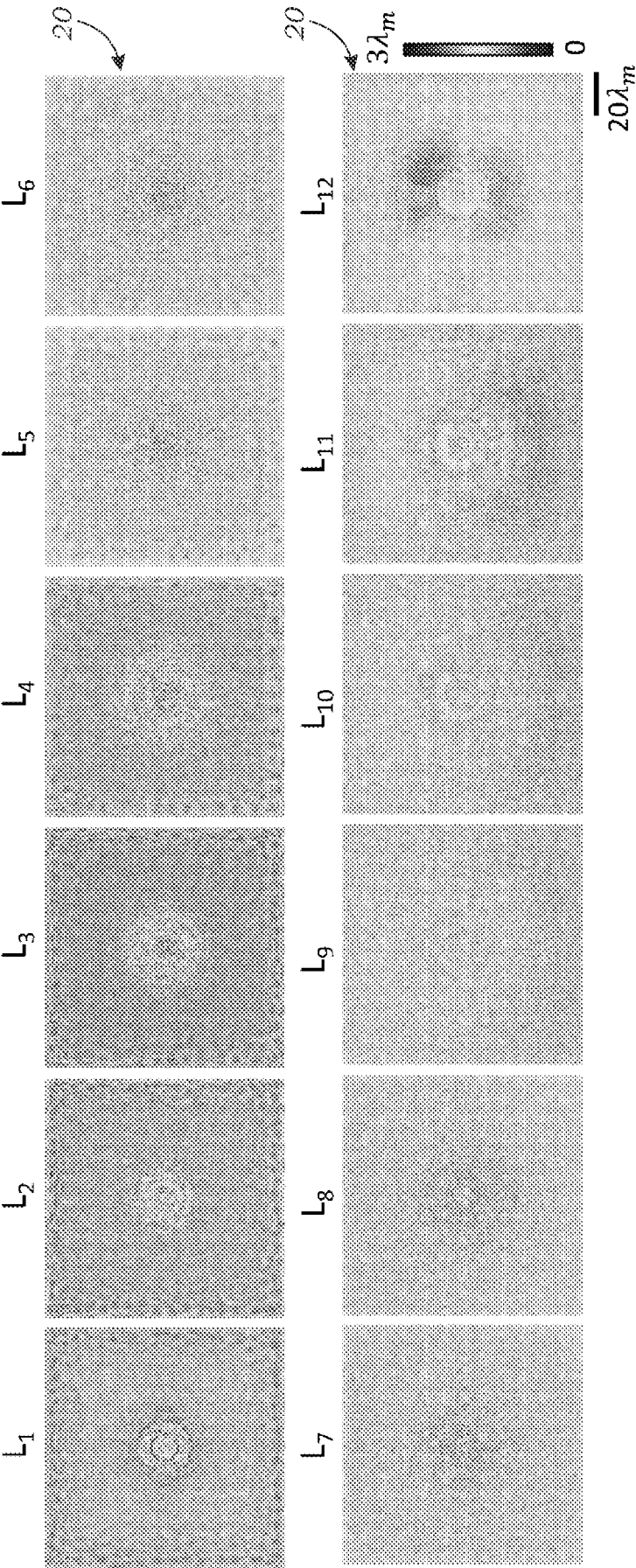


FIG. 17B

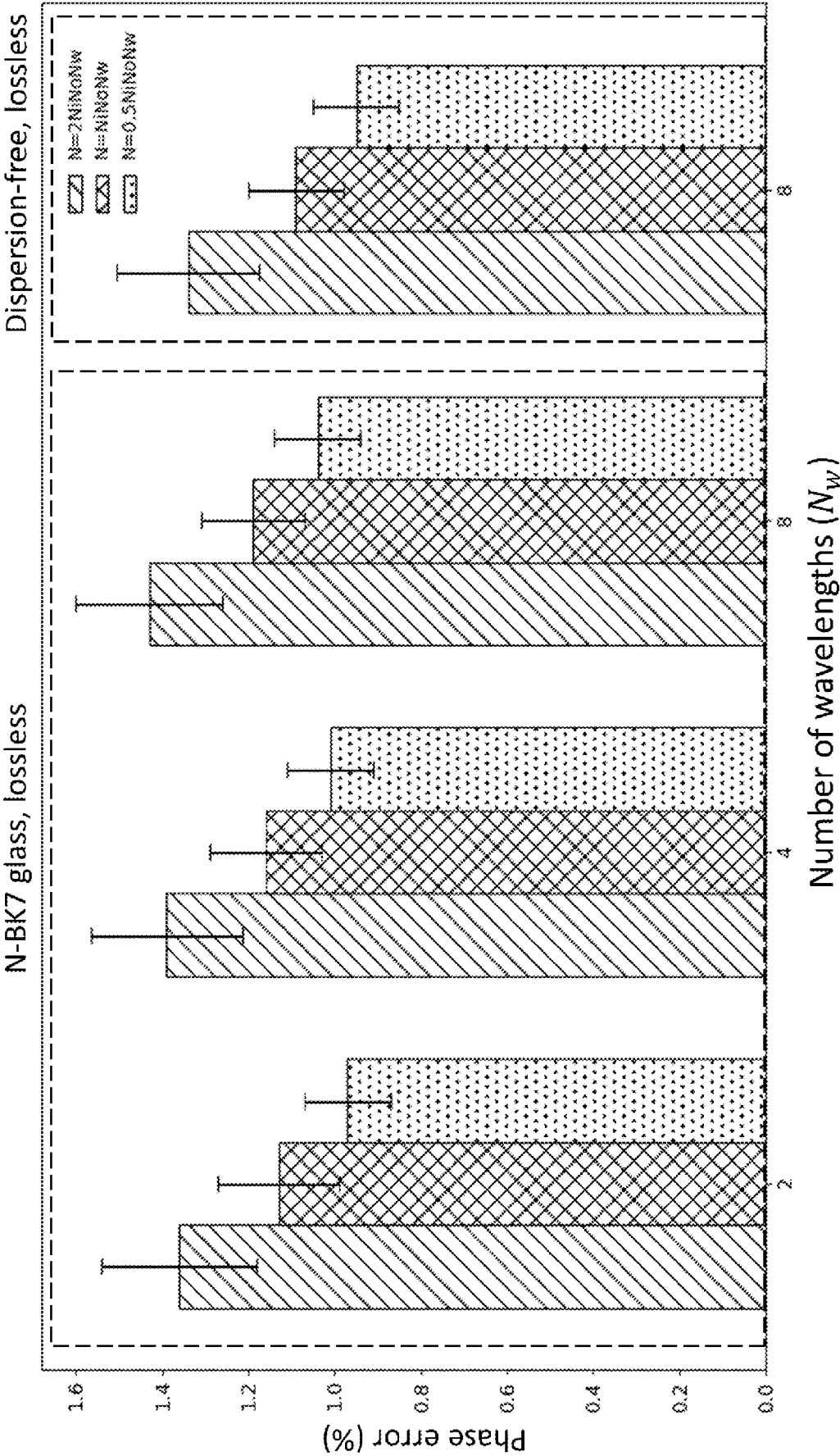


FIG. 18

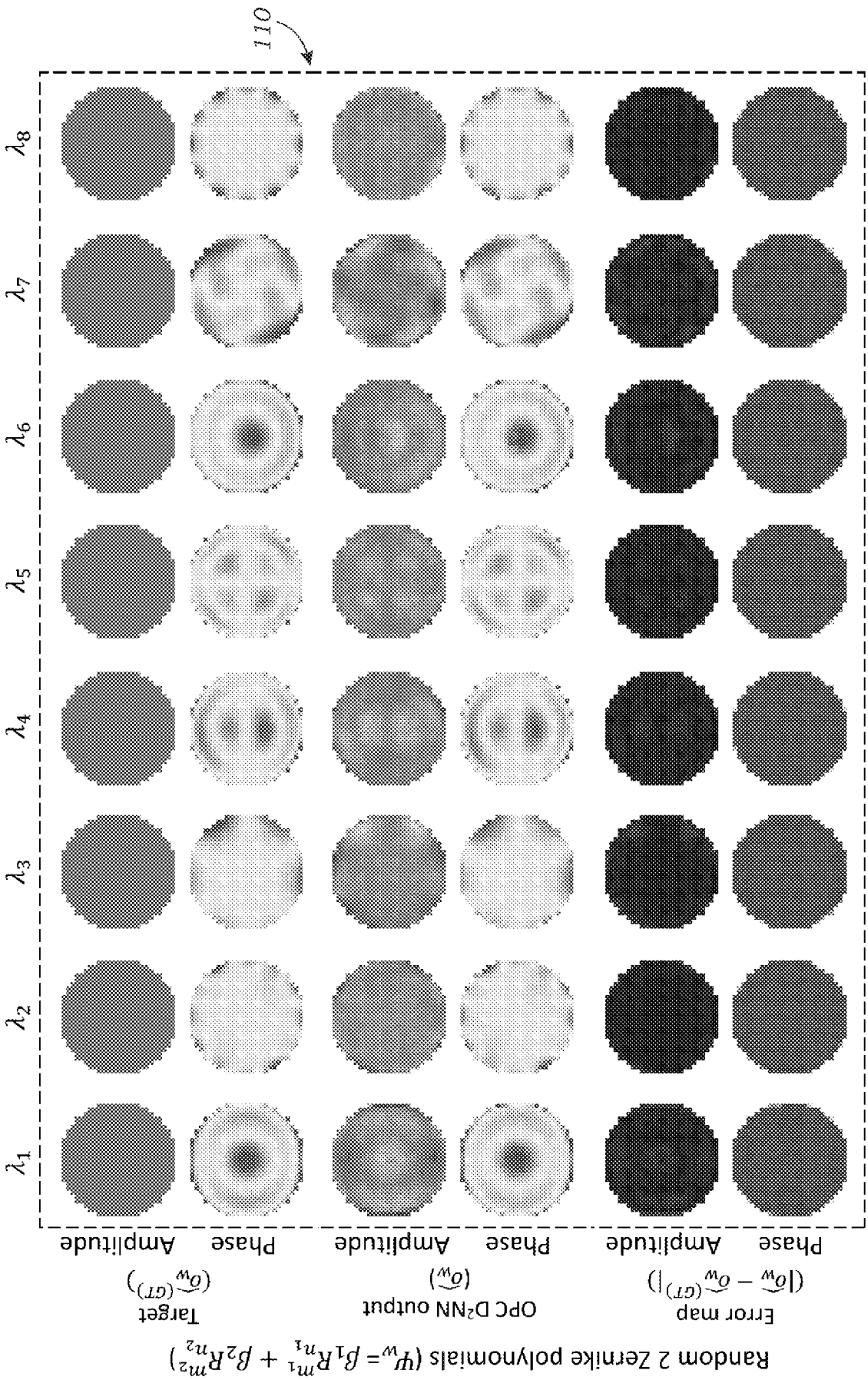


FIG. 19A

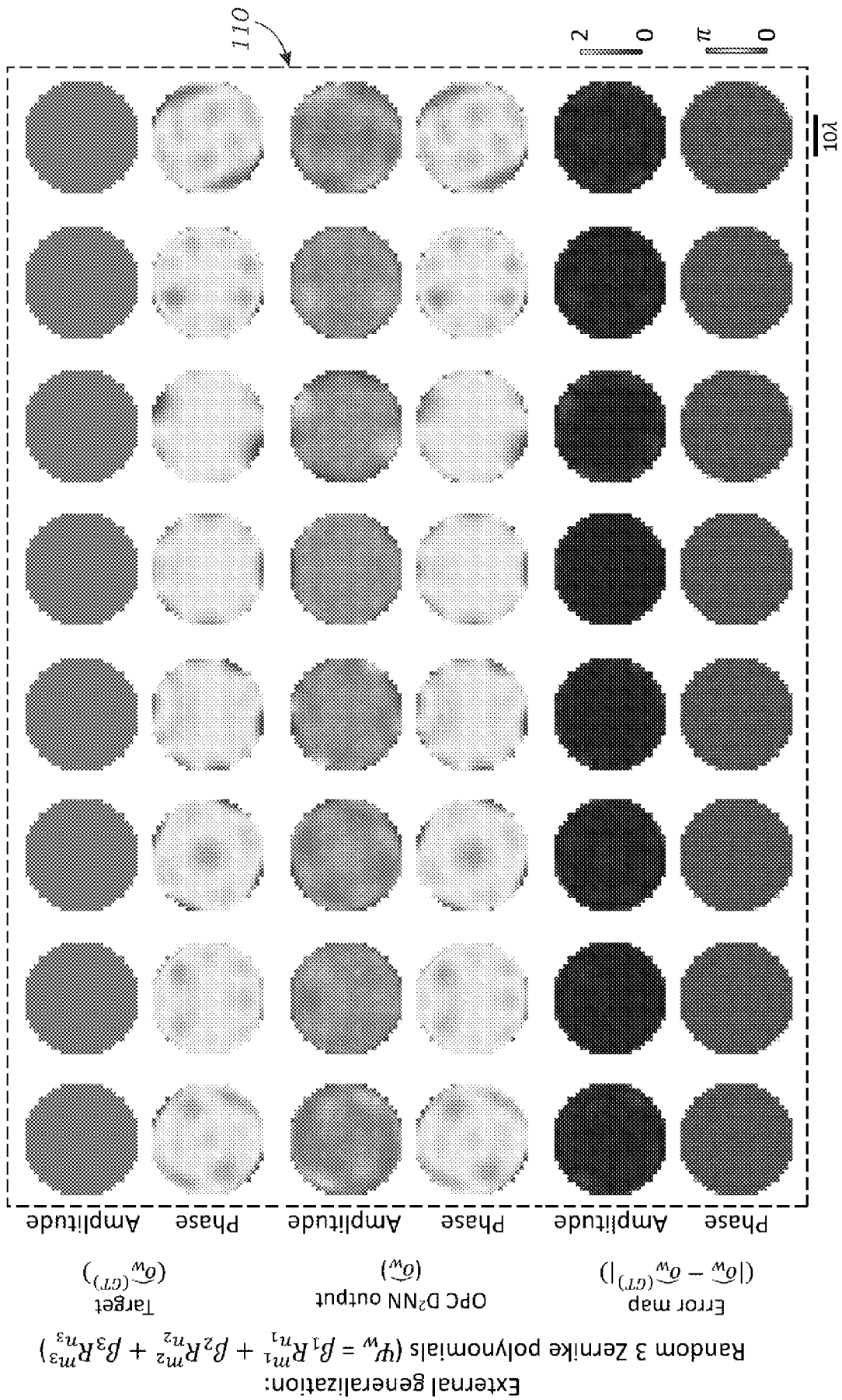


FIG. 19B

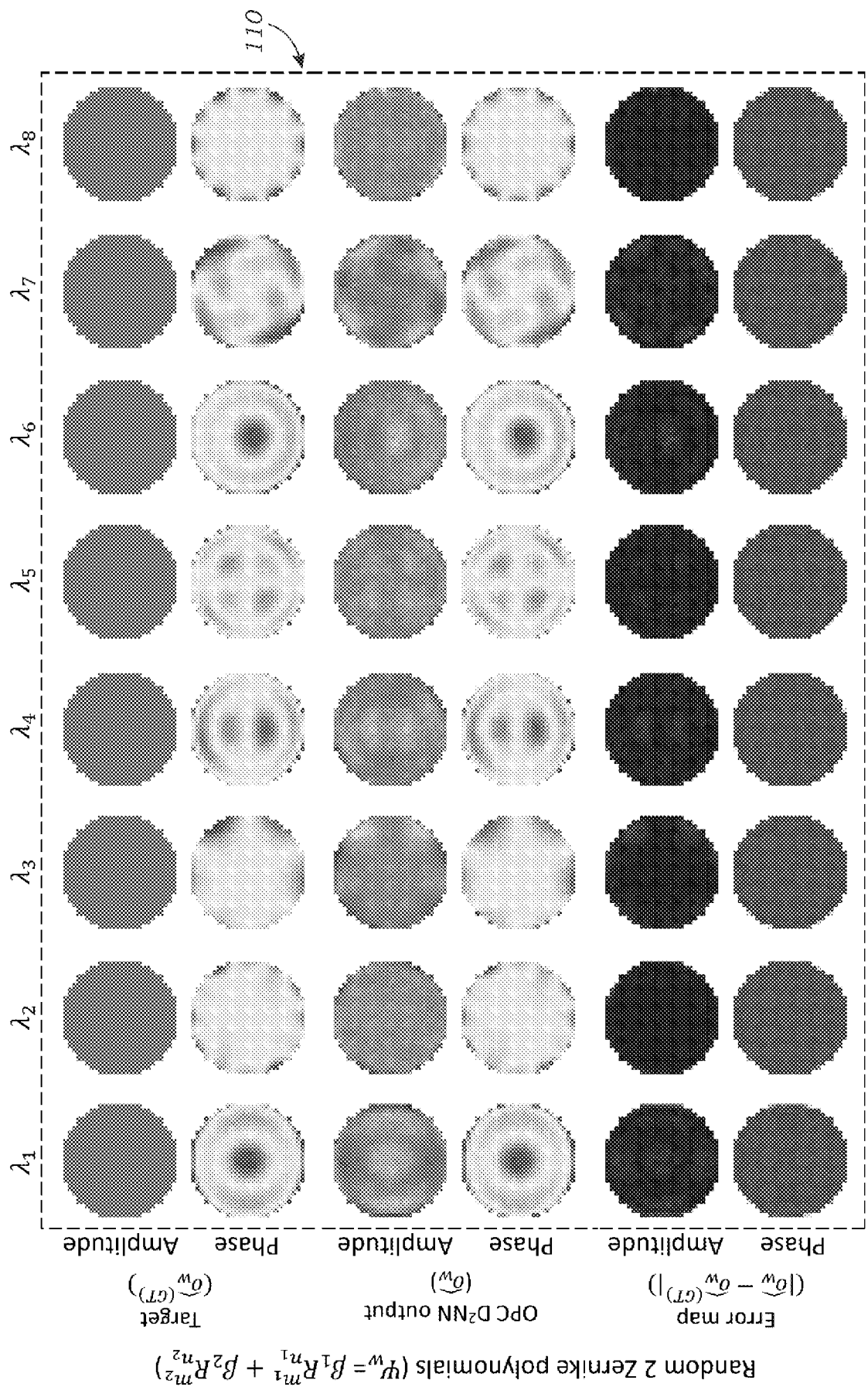


FIG. 20A

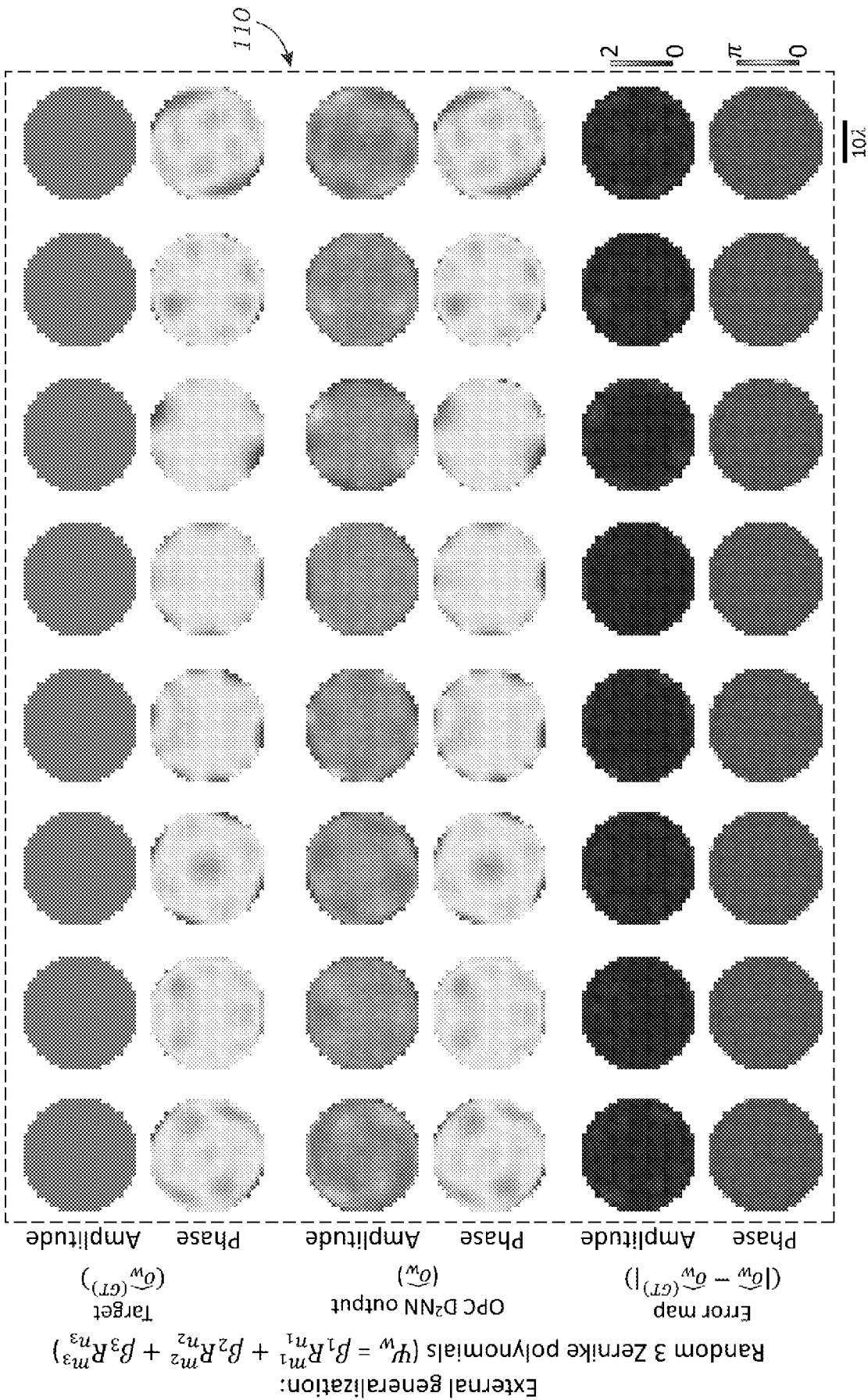
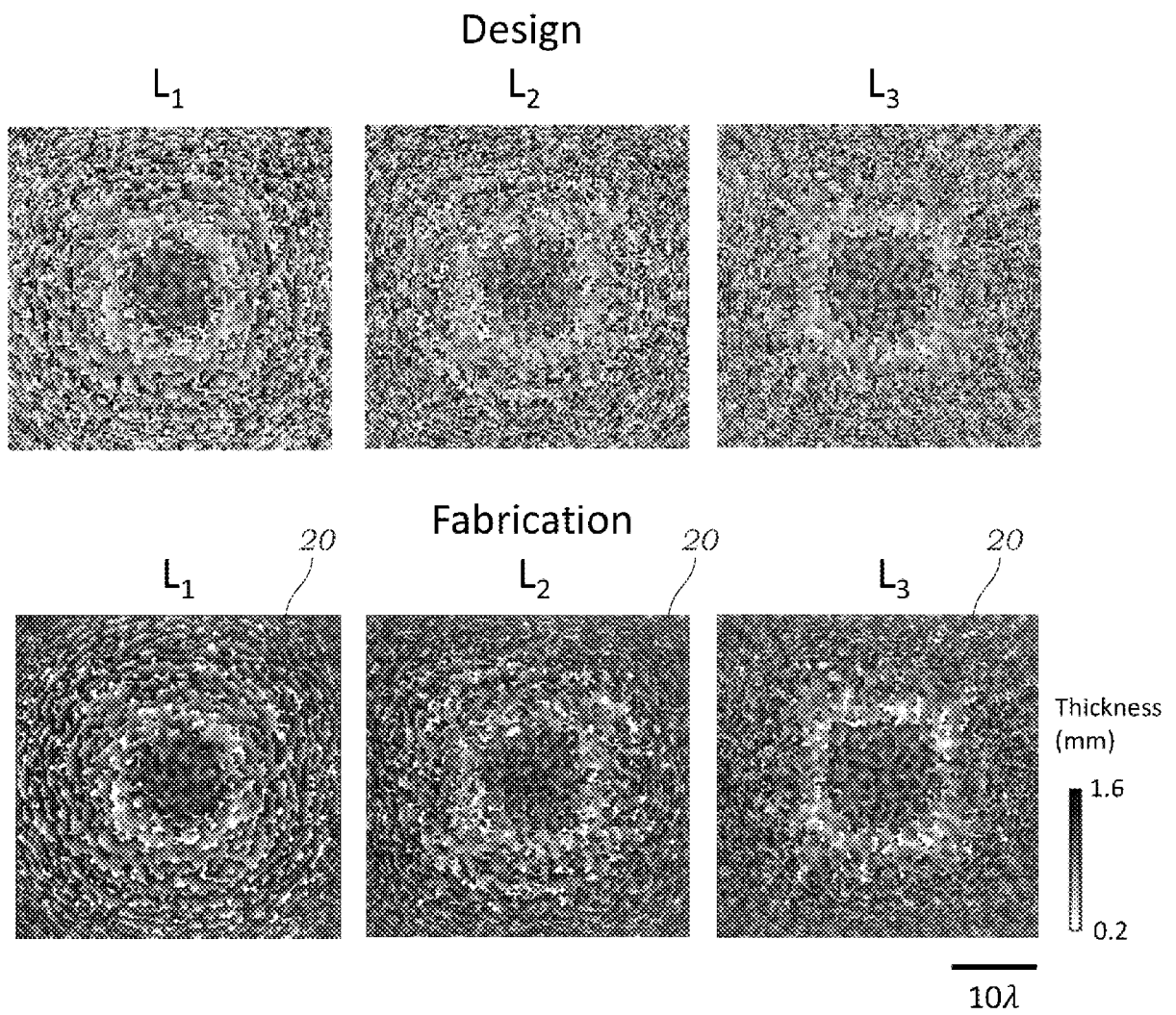


FIG. 20B

*FIG. 21A*

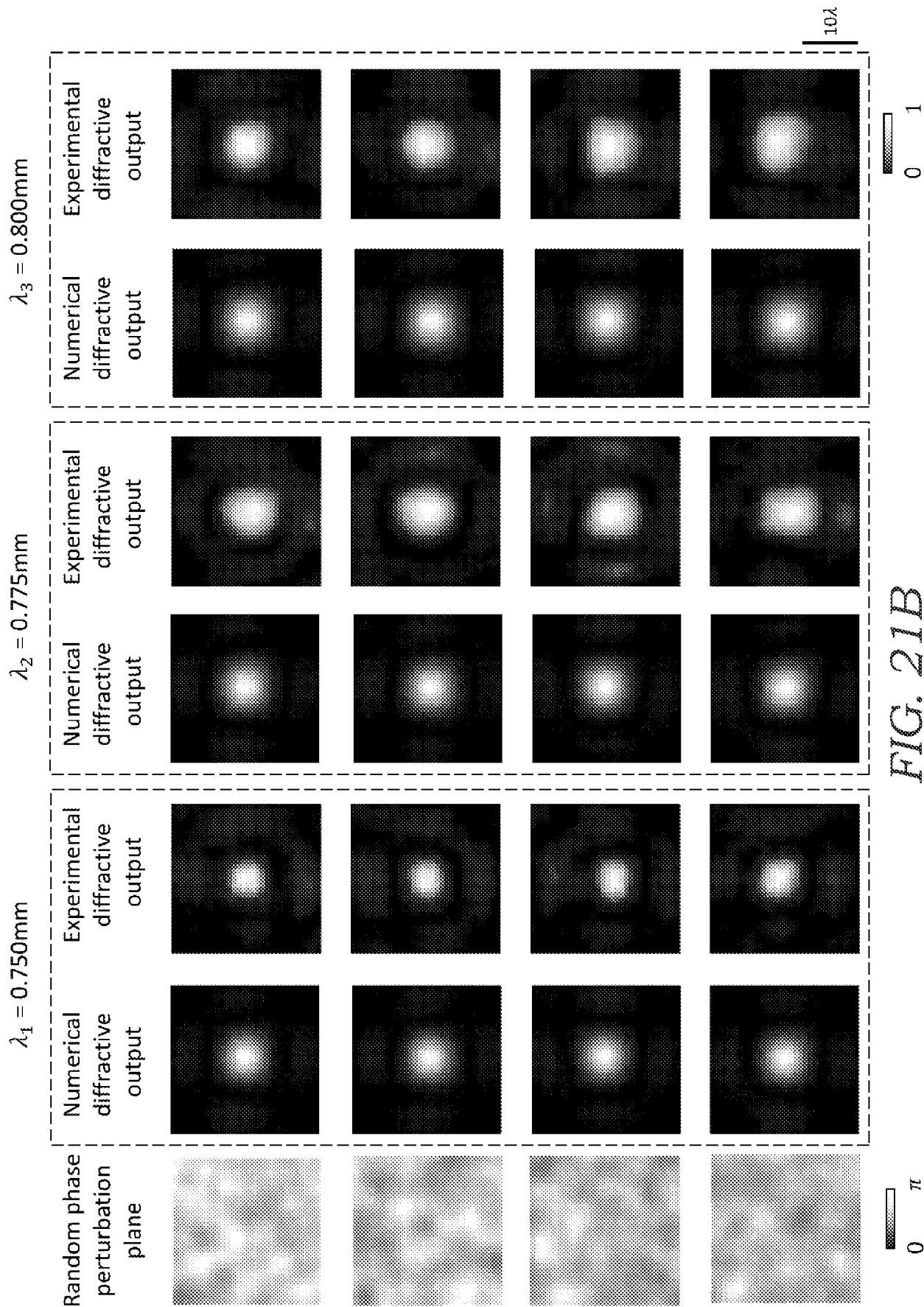


FIG. 21B

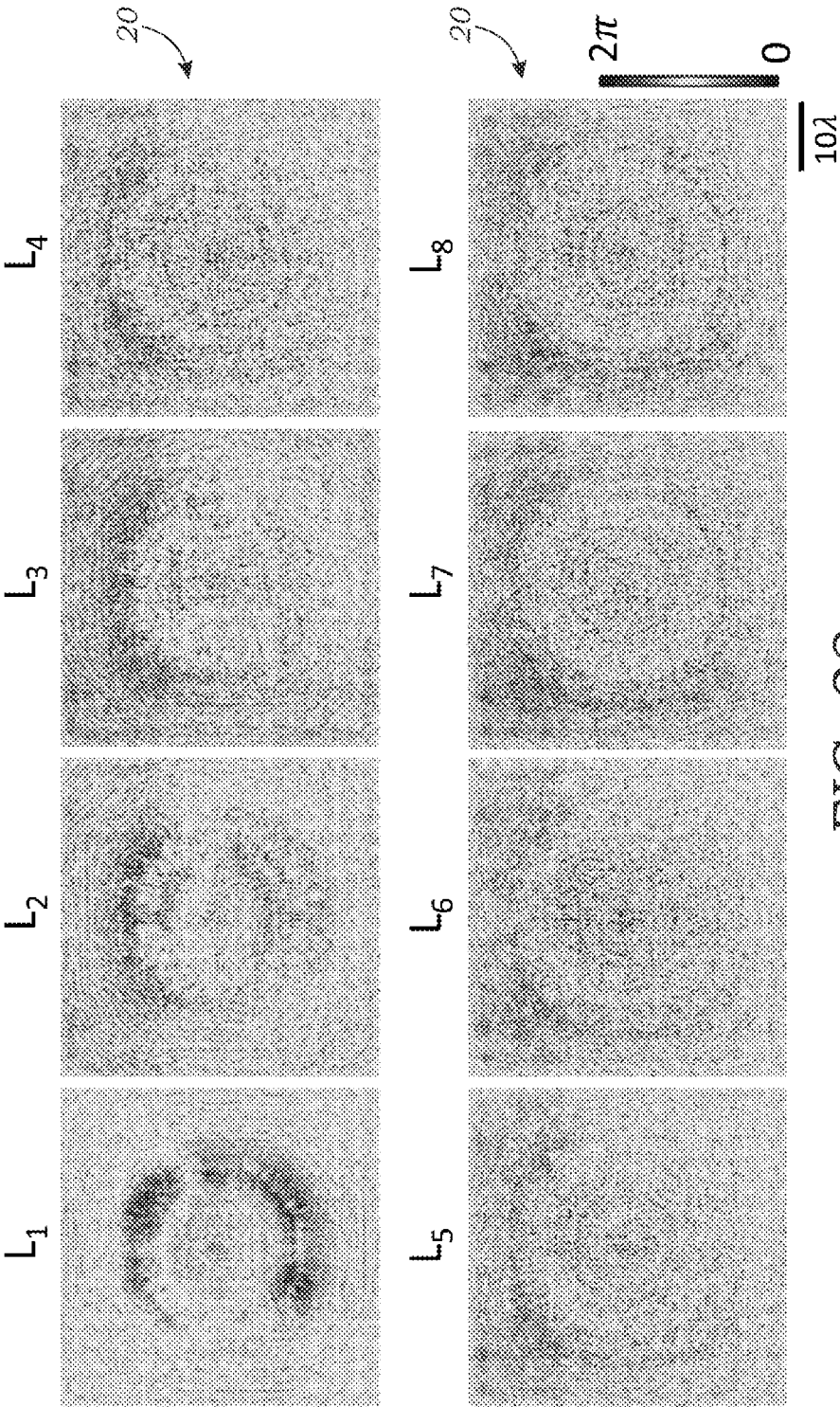
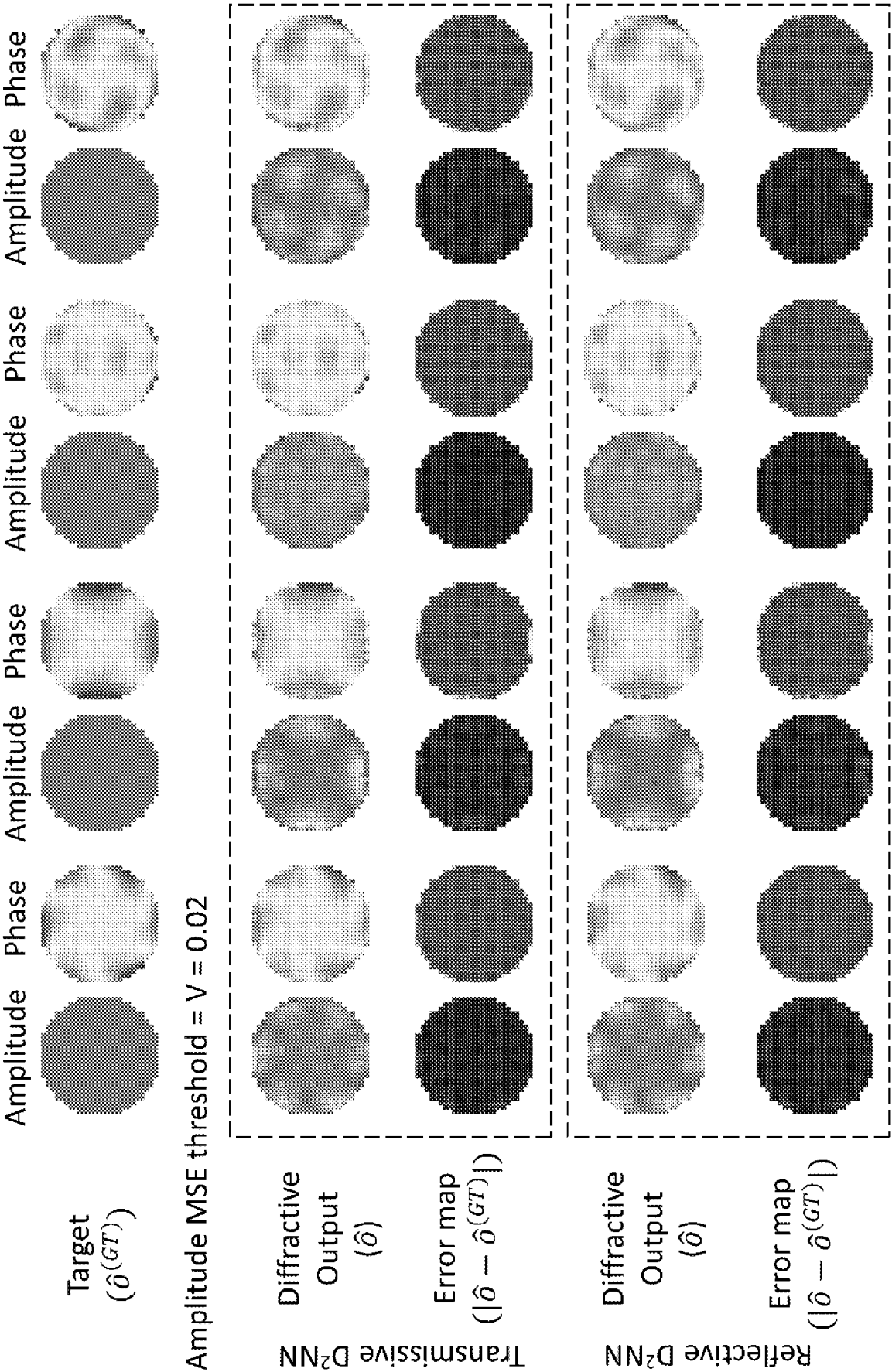


FIG. 22



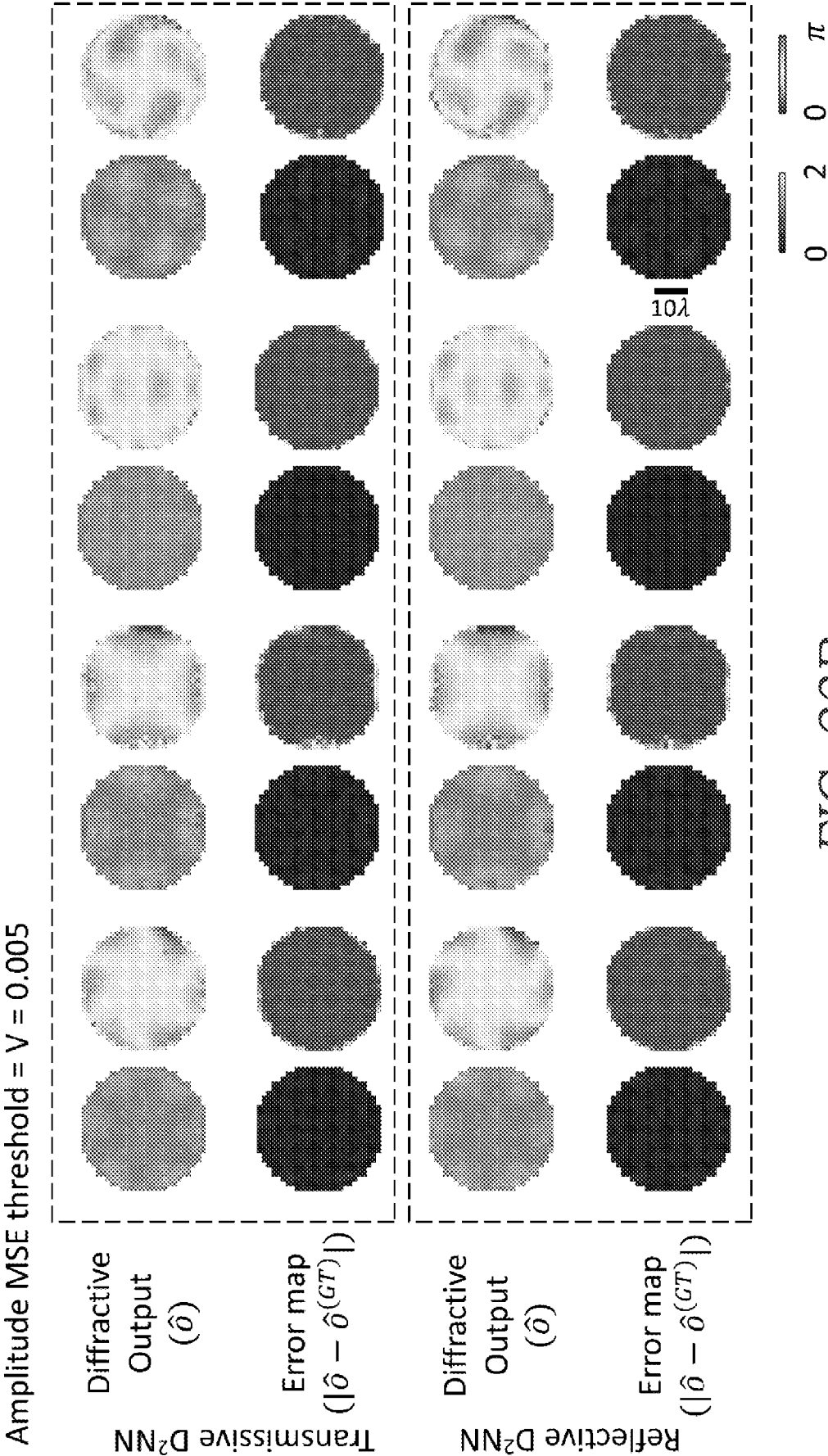


FIG. 23B

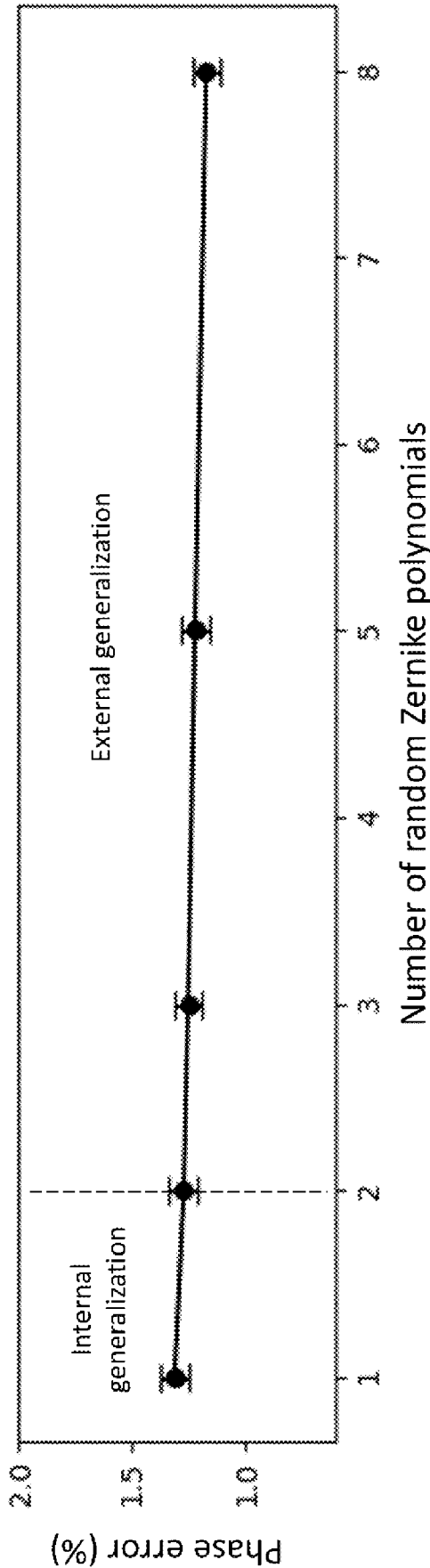


FIG. 24A

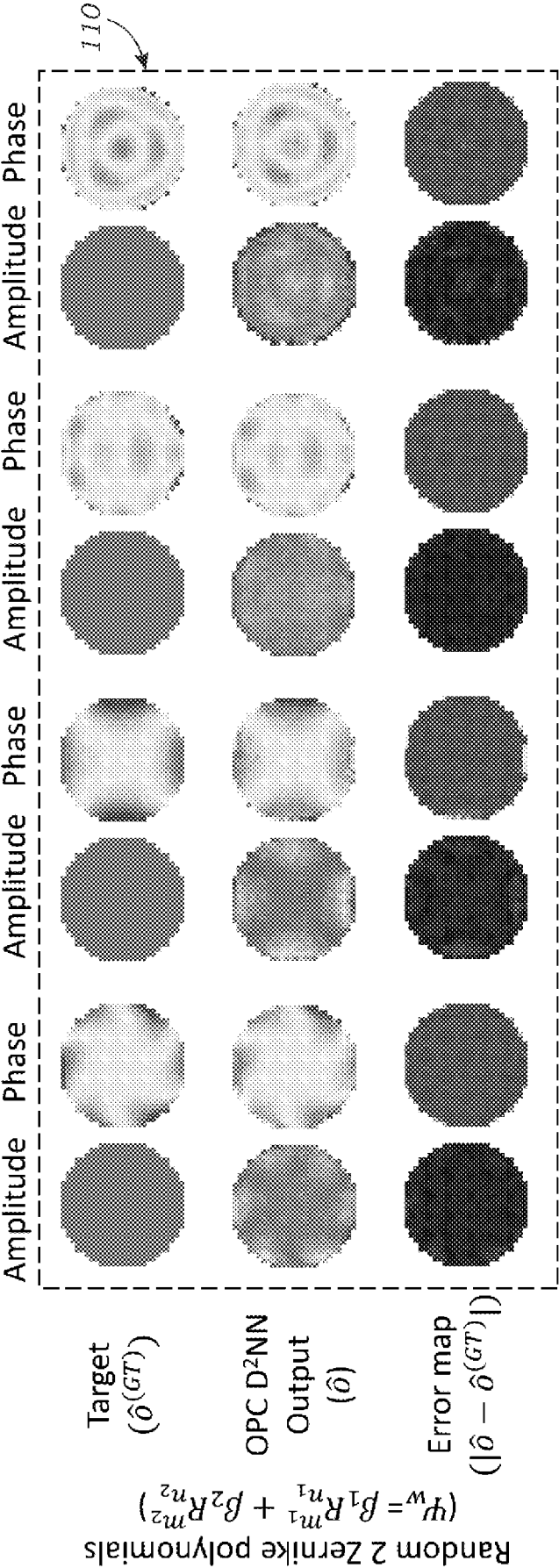


FIG. 24B

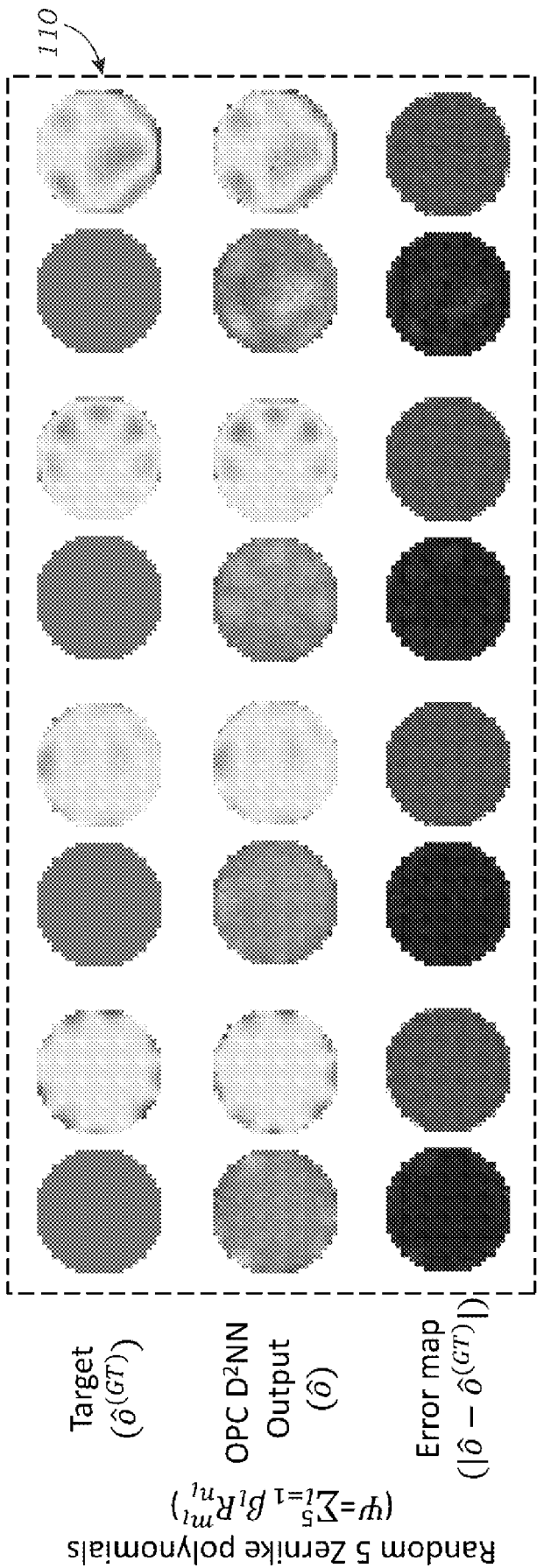


FIG. 24C

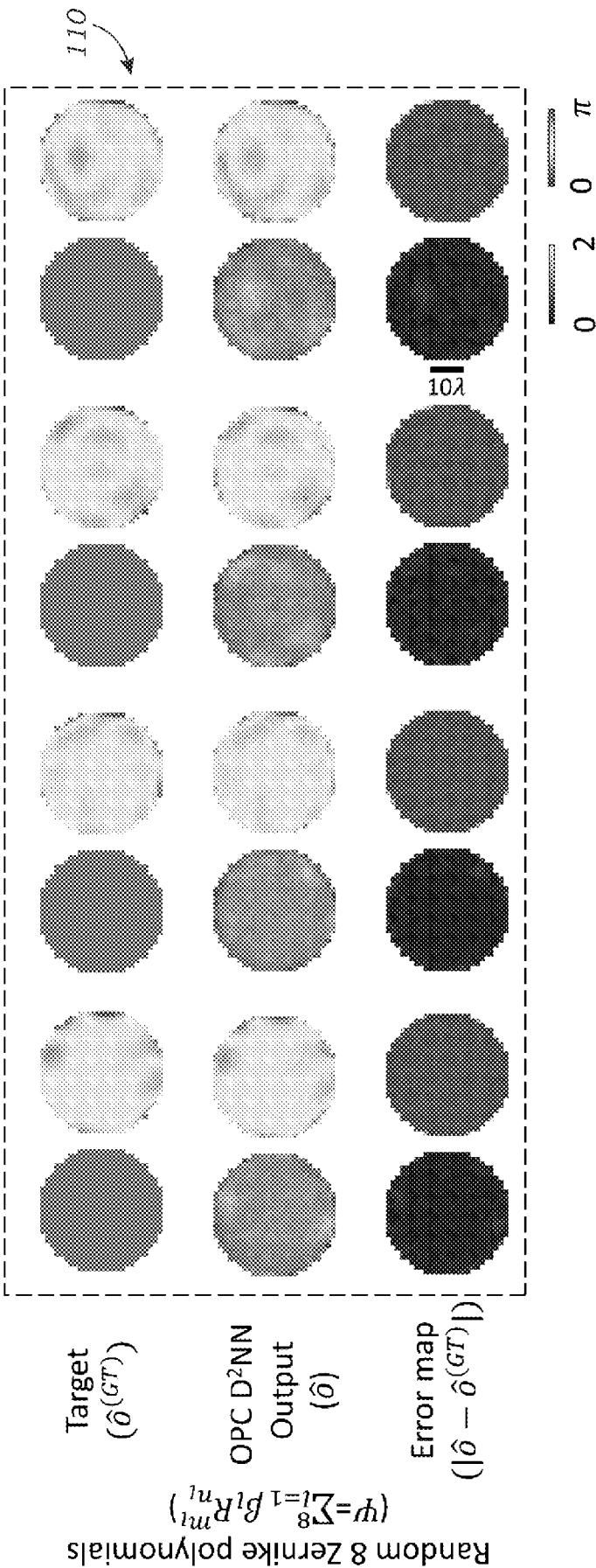


FIG. 24D

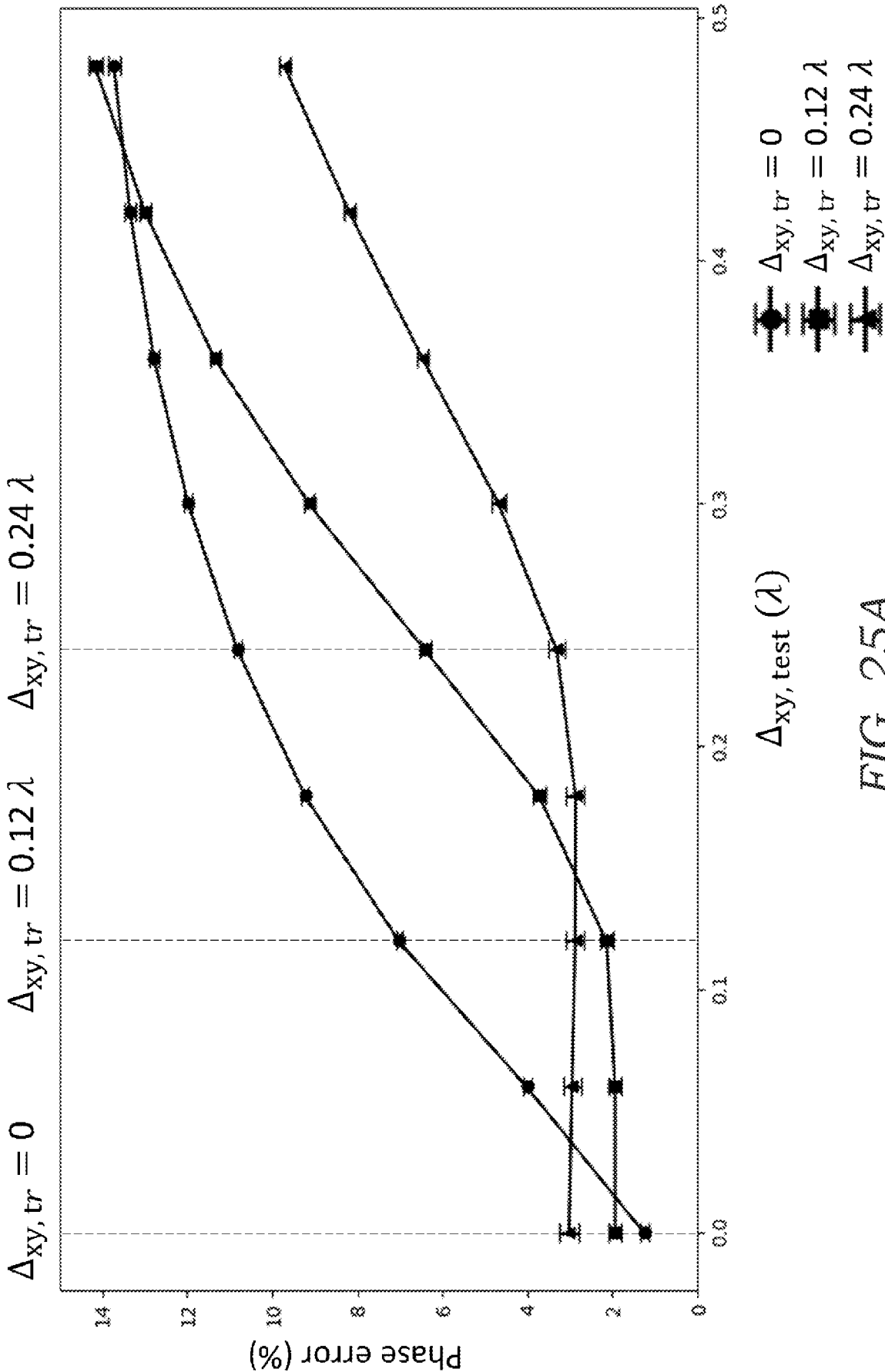


FIG. 25A

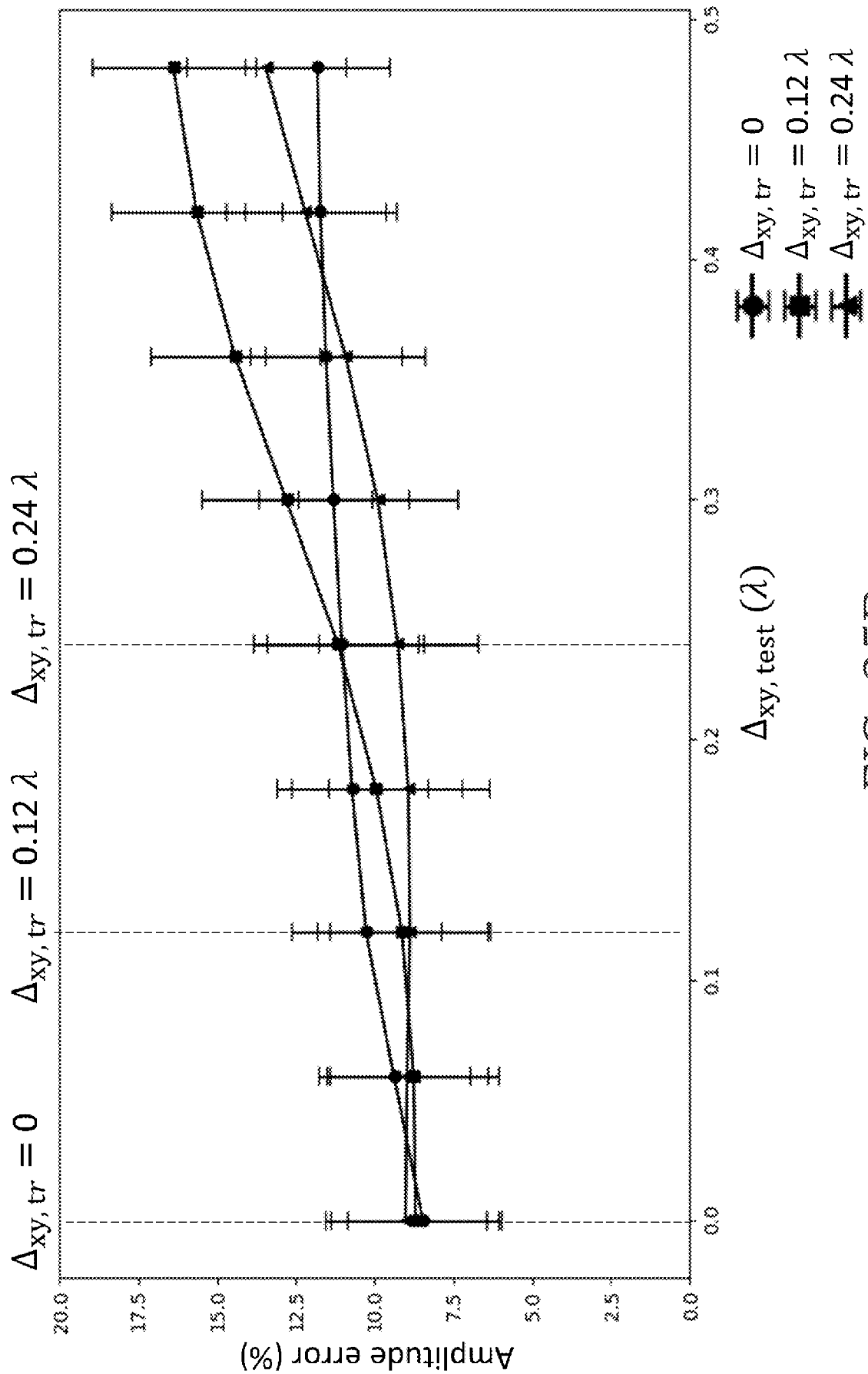


FIG. 25B

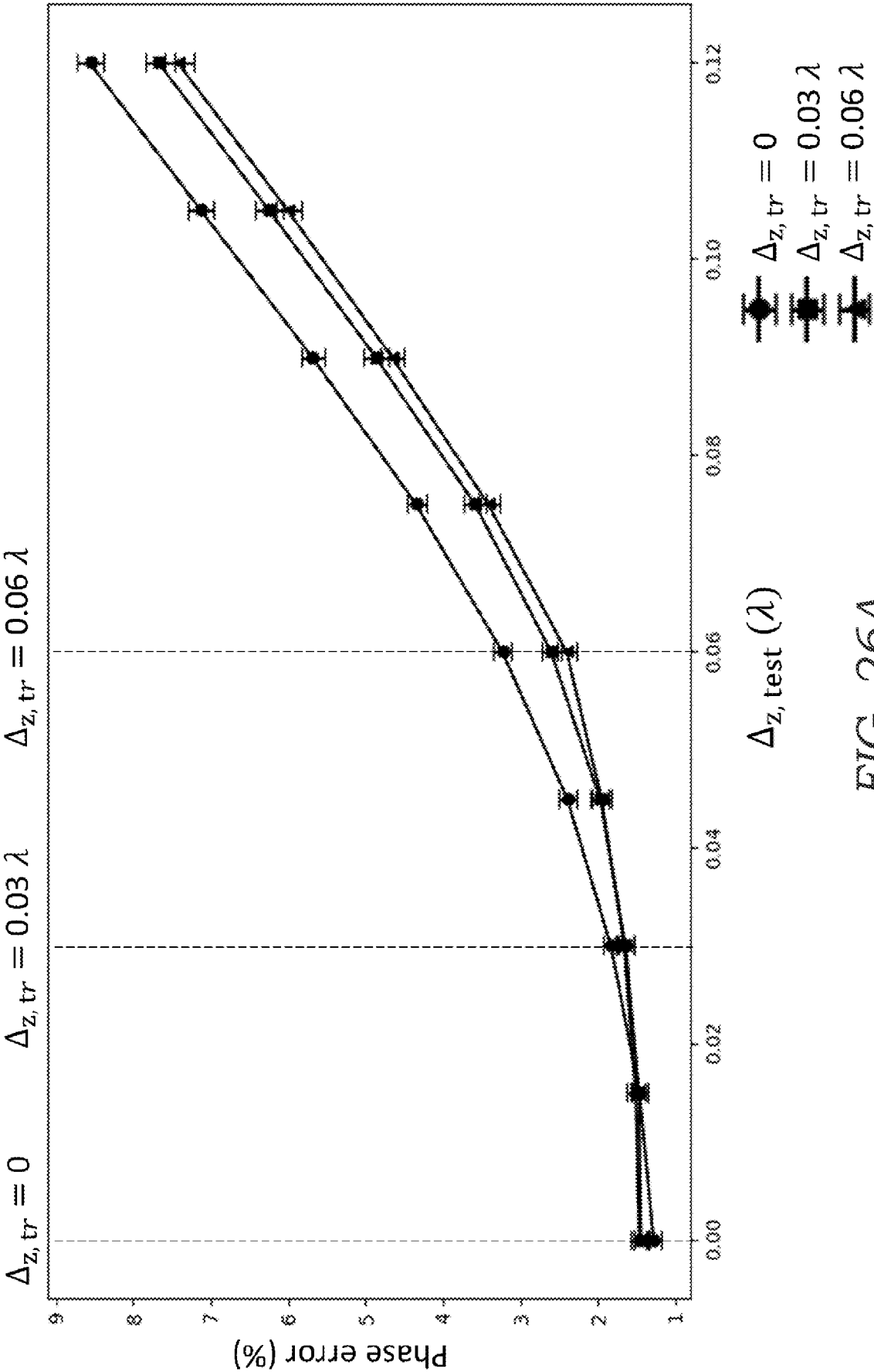


FIG. 26A

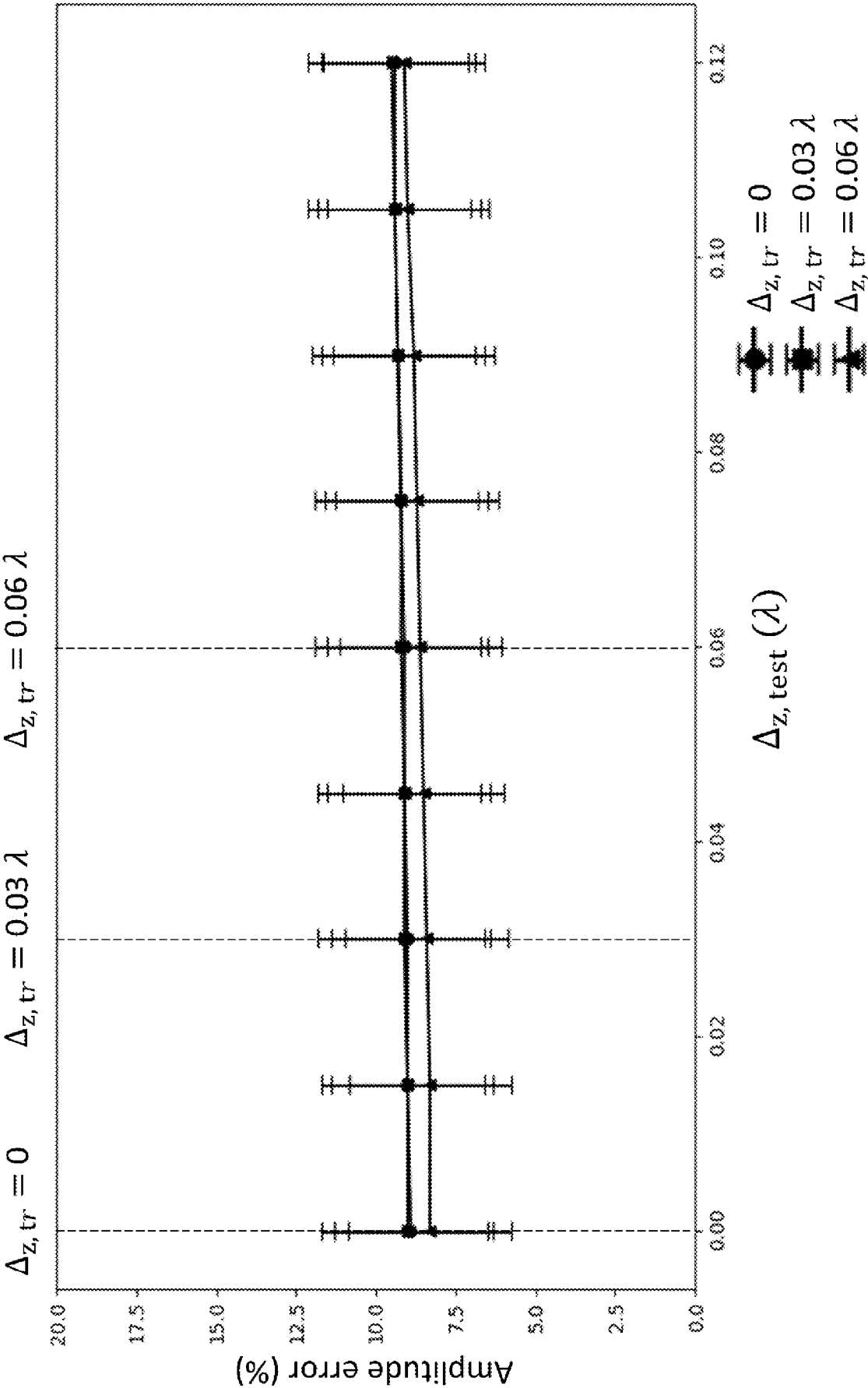
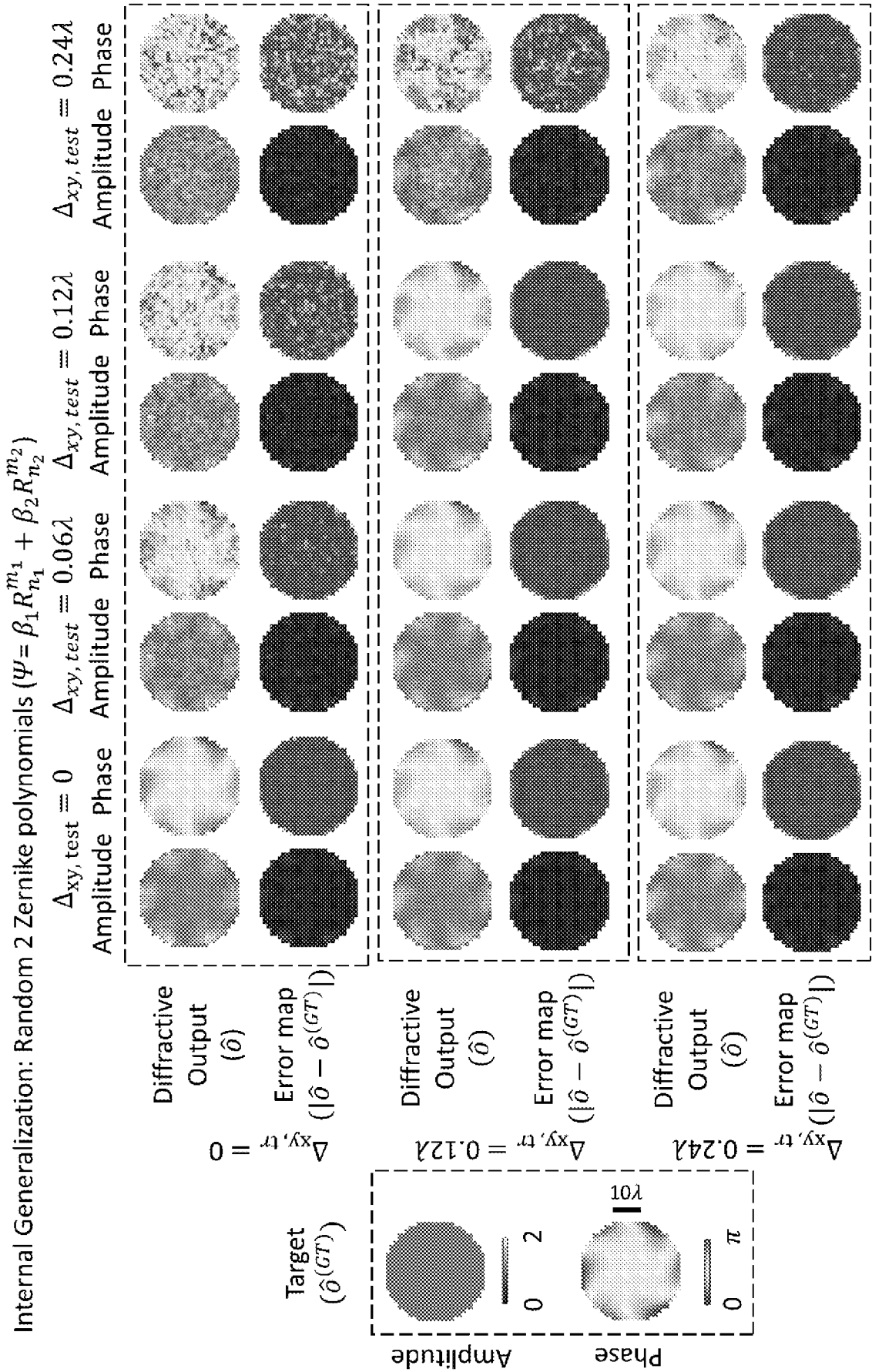


FIG. 26B



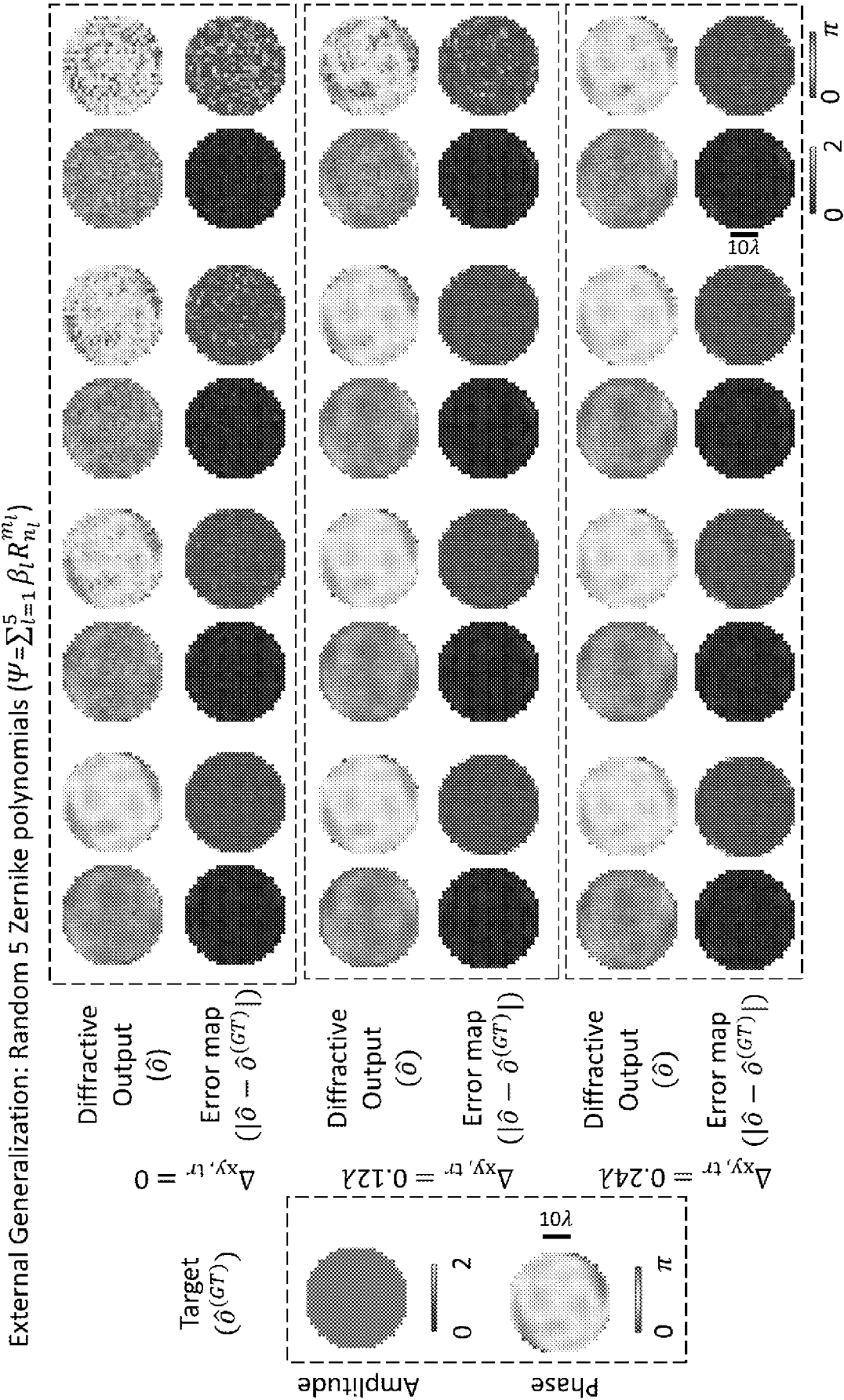


FIG. 27B

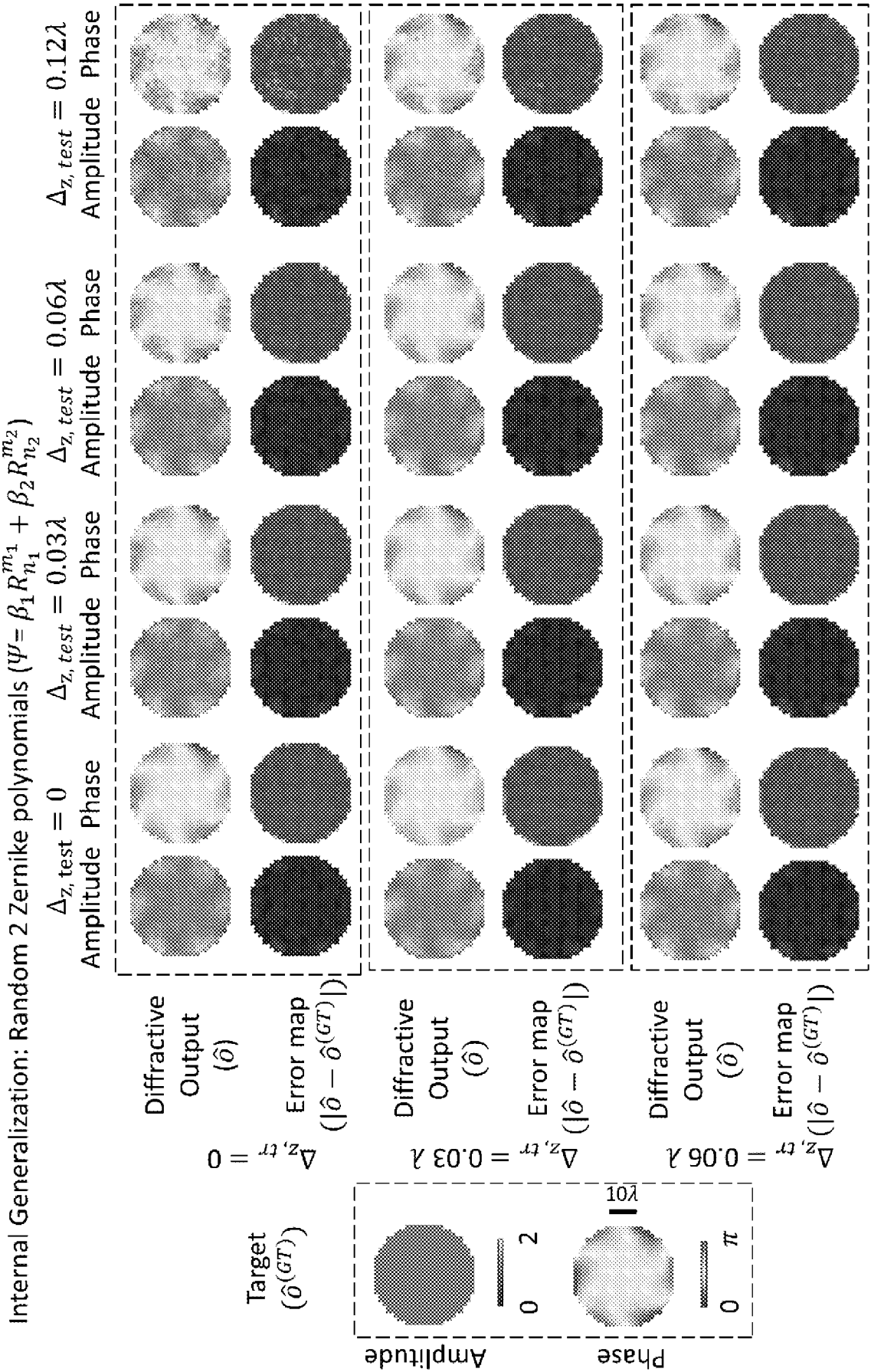


FIG. 28A

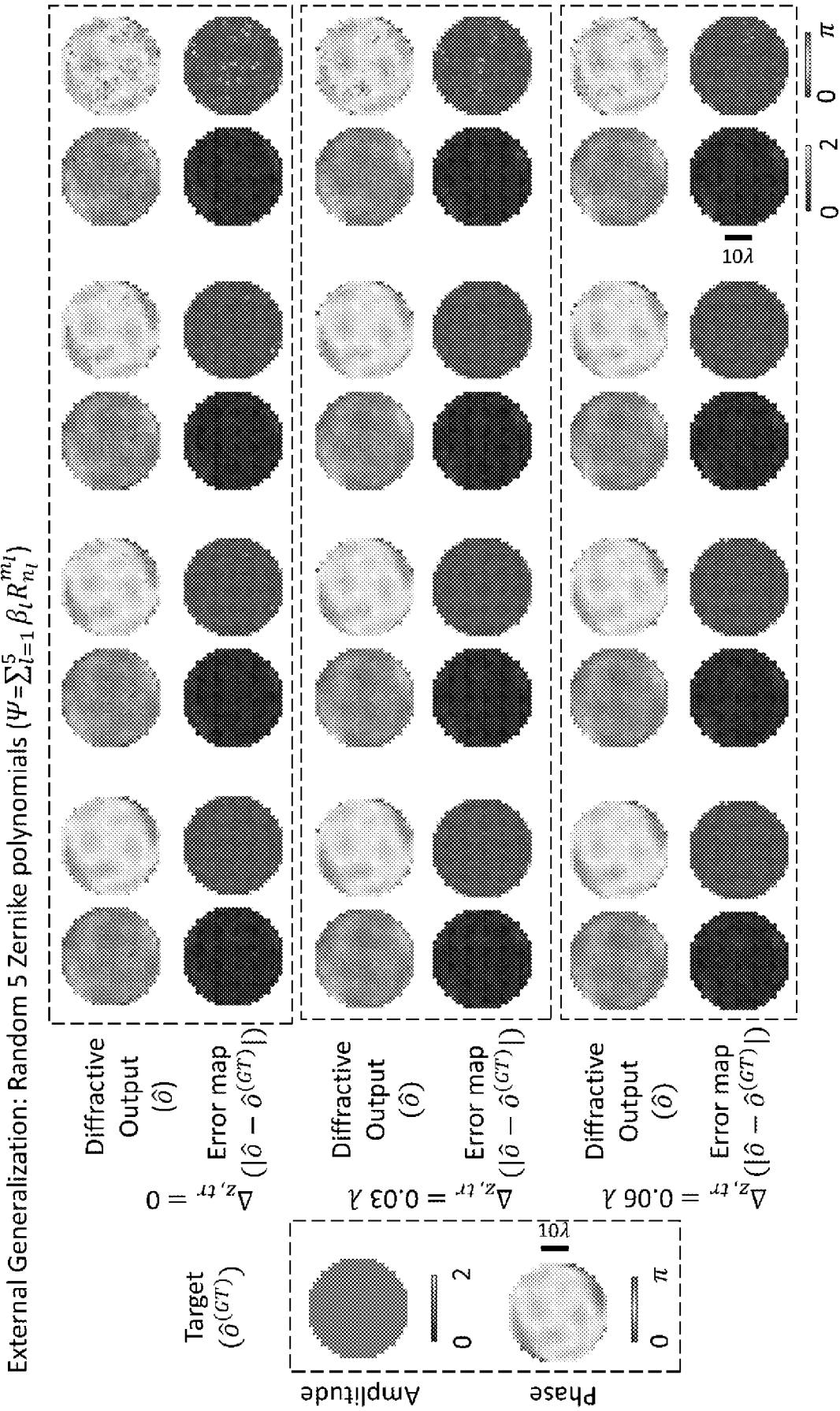


FIG. 28B

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/054791

A. CLASSIFICATION OF SUBJECT MATTER IPC: G02F 1/01 (2024.01); G06N 3/067 (2024.01); G02B 5/18 (2024.01); G02B 26/06 (2024.01) CPC: G02F 1/01 ; G02B 5/1814 ; G06N 3/067 ; G02B 26/06 According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) See Search History Document Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched See Search History Document Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) See Search History Document		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2019/0212544 A1 (FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V. et al.) 11 July 2019 (11.07.2019) entire document entire document	7, 8, 12 1-6, 9-11
Y	US 2019/0204611 A1 (THE BOARD OF TRUSTEES OF THE LELAND STANFORD JUNIOR UNIVERSITY) 04 July 2019 (04.07.2019) entire document	1-6
Y	US 2019/0113775 A1 (CALIFORNIA INSTITUTE OF TECHNOLOGY) 18 April 2019 (18.04.2019) entire document	2-4, 9-11
A	US 2021/0310787 A1 (CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE et al.) 07 October 2021 (07.10.2021) entire document	1-12
A	US 2008/0205461 A1 (HENRICHS) 28 August 2008 (28.08.2008) entire document	1-12
☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
* Special categories of cited documents: “A” document defining the general state of the art which is not considered to be of particular relevance “D” document cited by the applicant in the international application “E” earlier application or patent but published on or after the international filing date “L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) “O” document referring to an oral disclosure, use, exhibition or other means “P” document published prior to the international filing date but later than the priority date claimed “T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention “X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone “Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art “&” document member of the same patent family		
Date of the actual completion of the international search 14 December 2024 (14.12.2024)		Date of mailing of the international search report 26 December 2024 (26.12.2024)
Name and mailing address of the ISA/US COMMISSIONER FOR PATENTS MAIL STOP PCT, ATTN: ISA/US P.O. Box 1450 Alexandria, VA 22313-1450 UNITED STATES OF AMERICA Facsimile No. 571-273-8300		Authorized officer TAINA MATOS Telephone No. 571-272-4300

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/054791

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2015/0340835 A1 (LAWRENCE LIVERMORE NATIONAL SECURITY LLC) 26 November 2015 (26.11.2015) entire document	1-12
A	US 2021/0255488 A1 (THE REGENTS OF THE UNIVERSITY OF COLORADO A BODY CORPORATE) 19 August 2021 (19.08.2021) entire document	1-12