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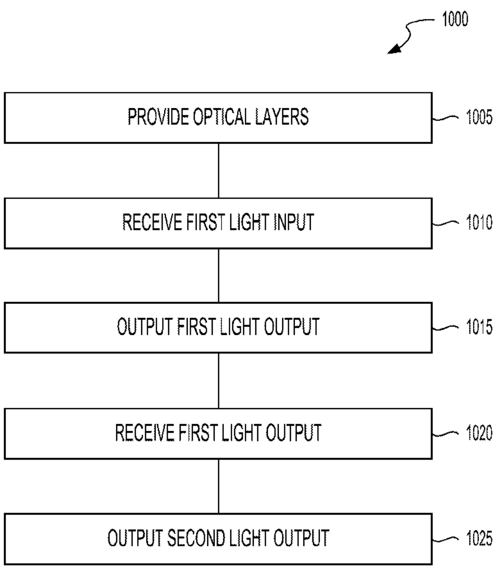

FIG. 10

(57) Abstract: A system can include a plurality of optical layers. Each optical layer of the plurality of optical layers can include an optical filter and a lens. The optical filter can have a transmission coefficient. The optical filter can receive a first light input. The optical filter can output a first light output including the first light input scaled by the transmission coefficient. The lens can receive the first light output. The lens can output a second light output that forms a Fourier transform of the first light output.

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SYSTEMS AND METHODS FOR DIFFERENTIABLE OPTICAL PROCESSORS

CROSS-REFERENCE TO RELATED PATENT APPLICATION

[0001] This application claims the benefit and priority of U.S. Provisional Patent Application No. 63/456,416, filed on March 31, 2023, the entirety of which is incorporated by reference herein.

GOVERNMENT RIGHTS

[0002] This invention was made with government support under MH130067 awarded by National Institutes of Health (NIH). The government has certain rights in this invention.

TECHNICAL FIELD

[0003] The present application relates generally to optical processors.

BACKGROUND

[0004] Optical signals can be processed at the speed of light.

SUMMARY

[0005] At least one aspect of the present disclosure is directed to a system. The system can include a plurality of optical layers. Each optical layer of the plurality of optical layers can include an optical filter and a lens. The optical filter can have a transmission coefficient. The optical filter can receive a first light input. The optical filter can output a first light output including the first light input scaled by the transmission coefficient. The lens can receive the first light output. The lens can output a second light output that forms a Fourier transform of the first light output.

[0006] Another aspect of the present disclosure is directed to a method. The method can include providing a plurality of optical layers each comprising an optical filter and a lens. The method can include receiving, by the optical filter, a first light input, the optical filter having a transmission coefficient. The method can include outputting, by the optical filter, a first light output comprising the first light input scaled by the transmission coefficient. The method can include receiving, by the lens, the first light output. The method can include outputting, by the lens, a second light output that forms a Fourier transform of the first light output.

[0007] Those skilled in the art will appreciate that the summary is illustrative only and is not intended to be in any way limiting. Other aspects, inventive features, and

advantages of the devices and/or processes described herein, as defined solely by the claims, will become apparent in the detailed description set forth herein and taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the subject matter will become apparent from the description, the drawings, and the claims.

[0009] FIG. 1A illustrates an optical layer, according to an embodiment.

[0010] FIG. 1B illustrates a system for differentiable optical processors, according to an embodiment.

[0011] FIG. 2 illustrates a system for differentiable optical processors, according to an embodiment.

[0012] FIG. 3A illustrates a system for differentiable optical processors, according to an embodiment.

[0013] FIG. 3B illustrates a system for differentiable optical processors, according to an embodiment.

[0014] FIG. 3C illustrates a system for differentiable optical processors, according to an embodiment.

[0015] FIG. 4 illustrates detector regions, according to an embodiment.

[0016] FIGS. 5A-5C illustrate all-optical quantitative phase imaging via differentiable optical processors, according to an embodiment.

[0017] FIGS. 6A-6C illustrate coherent confocal imaging via differentiable optical processors, according to an embodiment.

[0018] FIG. 7A illustrates a linearly separable dataset, according to an embodiment.

[0019] FIG. 7B illustrates a linearly inseparable dataset, according to an embodiment.

[0020] FIG. 8 illustrates a high-dimensional projection, according to an embodiment.

[0021] FIGS. 9A and 9B illustrate classification results for a linearly separable dataset.

[0022] FIGS. 9C and 9D illustrate classification results for a linearly inseparable dataset.

[0023] FIG. 10 illustrates a method of performing optical processing, according to an embodiment.

[0024] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0025] Following below are more detailed descriptions of various concepts related to, and implementations of methods and apparatuses for differentiable optical processors. The various concepts introduced above and discussed in greater detail below may be implemented in any of a number of ways, as the described concepts are not limited to any particular manner of implementation. Examples of specific implementations and applications are provided primarily for illustrative purposes.

[0026] Passive optics can process signals in parallel at the speed of light. Unlike in general purpose electronics, the cost of operations may not scale with the size of the signal being processed. Optical processers can perform various types of linear computations including the Fourier transform. Trained machine learning models can be implemented optically.

[0027] The systems and methods of the present disclosure are directed to differentiable optical processors. Differentiable optical processors can include a general optical neural network architecture that can be trained to perform tasks optically. The optical architecture can be morphed into a target optical processor or a function.

[0028] FIG. 1A illustrates an optical layer 100 (e.g., layer). The optical layer 100 can include one or more optical filters 105 (e.g., filters). The optical filter 105 can include a transmission coefficient. The transmission coefficient can be a learnable parameter. The transmission coefficient can be a weight of a model. The optical filter 105 can receive a first light input (e.g., first light field input). The optical filter 105 can output a first light output (e.g., first light field output). The first light output can include the first light input scaled by the transmission coefficient.

[0029] The optical layer 100 can include one or more lenses 110. The lens 110 can receive the first light output. The first light output can be E_{in_T}. The lens 110 can output a second light output. The second light output can form a Fourier transform of the first light output. The lens 110 can be in a 4f configuration. The lens 110 can include the lens f.

[0030] FIG. 1B illustrates a system 200. The system 200 can be for differentiable optical processors. The system 200 can include one or more optical processors (e.g., differentiable optical processors, optical transformers). The system 200 can include an optical module. The system 200 can include one or more optical layers 100. The system 200 can include a plurality of layers (e.g., N layers). For example, the system 200 can include a plurality of optical layers 100. The system 200 can include one or more optical transformers. The differentiable optical processors can include a scalable optical architecture that can perform arbitrary linear transforms. The system 200 can include a linear optical processor.

[0031] E_{in_T} can be the input to the layer. T can be the optical filter 105 with a transmission coefficient $T(x, y)$ at each (x, y) location. These transmission coefficients can be the learnable parameters (e.g. weights) of the model. Then the electric field just after T can be given Equation 1.

$$E_T(x, y) = T(x, y)\, E_{in\_T}(x, y) \tag{1}$$

[0032] The lens f can perform the Fourier transform on the field $E_t(x,y)$ at its Fourier plane as, $\mathbf{F}(E_t(x, y))\{U, V\}$. $\{U, V\}$ can include the spatial frequency components. The spatial frequency (U, V) can be located at $(x', y') = (\lambda fU, (\lambda fU)$ of the Fourier plane of "f." λ can include the wavelength of light and f can include the focal length of the lens f. Therefore, the electric field at the Fourier plane of 'f' can be given by Equation 2.

$$E_{out\_T}(x', y') = C\, \boldsymbol{F}\left(T(x, y).\, E_{in\_T}(x, y)\right)\left\{\frac{x'}{\lambda f}, \frac{y'}{\lambda f}\right\} \tag{2}$$

[0033] The plurality of optical layers 100 can include a first optical layer 100. The plurality of optical layers 100 can include a second optical layer 100. The first optical layer 100 can be adjacent to the second optical layer 100. The second light output can be received by an adjacent layer of the plurality of optical layers 100. For example, the first optical layer 100 can output the second light output. The second optical layer 100 can receive the second light output. The plurality of optical layers 100 can be cascaded.

[0034] For the representative model shown in FIG. 1B, $E_{in}(x, y)$ can be the input field. This can be the input field, $E_{in\_T1}(x, y)$, to the first layer with the filter T_1. The output field from the first layer $E_{out}(x', y')$ can become the input to the T_2 and the same process can repeat

N times till T_N. The output field from the last layer $E_{out\_TN}(x',y')$ can be the output, $E_{out}(x,y)$, of the model.

[0035] FIG. 2 illustrates the system 200. The system 200 can include an optical module. For example, the system 200 can include an optical module with skip connections. The system 200 can include a reference beam path (e.g., reference path, skip-connection arm, reference). The reference path can serve various purposes. For example, the reference path can act as a skip connection so that the model can be efficiently trained. The reference path can overlap Fourier and image planes to a single z-location so that the model capacity can be increased compared to the architecture shown in FIG. 1B. Similar to the transformer module shown in FIG. 1B, multiple layers can be cascaded to build a large model. The model can be linear. The system 200 can be linear.

[0036] The system 200 can include the lens 110. The lens 110 can include the lens f_1. The The lens 110 can include the lens f_2. The lens 110 can include the lens f_3. The lens f_2 can be in a 4f configuration. The lens f_3 can be in a 4f configuration. The lens f_1 can be in a 2f configuration. All equations can be written for the electric fields at the image planes and/or Fourier planes.

[0037] After the beam splitter BS_1, on the filter arm (e.g., that goes to **T**), the electric field just before the optical filter **T** can be given by Equation 3.

$$E_T = \frac{E_{in}}{4} + \frac{E_{in}}{4} = \frac{E_{in}}{2} \tag{3}$$

[0038] The electric field just after the optical mask **T** can be given by Equation 4.

$$E_T = \frac{E_{in}}{2}\,\boldsymbol{T} \tag{4}$$

[0039] After the beam splitter BS_1, on the skip-connection arm, the electric field can be given by Equation 5.

$$E_{skp} = \frac{E_{in}}{2} \tag{5}$$

[0040] The output electric fields E_{out1} and E_{out2} can be written as Equation 6 and Equation 7, respectively. The output electric fields can be projected to the next stage's image plane and/or Fourier plane.

$$E_{out1} = \frac{E_{skp}}{2} + \frac{F(E_{T})}{2} \tag{6}$$

$$E_{out2} = \frac{F(E_{T})}{2} + \frac{E_{skp}}{2} \tag{7}$$

[0041] $\boldsymbol{F}$ can be the Fourier transform. Equation 8 can be defined as the following.

$$\frac{E_{out}}{2} = E_{out1} = E_{out2} \tag{8}$$

[0042] Equation 9 and Equation 10 can include the following.

$$\frac{E_{out}}{2} = \frac{1}{2}\left(\boldsymbol{F}\left(\frac{E_{in}}{2}\boldsymbol{T}\right) + \frac{E_{in}}{2}\right) \tag{9}$$

$$E_{out} = \frac{1}{2}\,(\boldsymbol{F}(R_{in}\boldsymbol{T}) + E_{in}) \tag{10}$$

[0043] Thus, an optical module with a skip connection can be achieved. Note that light is not lost in this configuration despite having beam splitters.

[0044] Each optical layer 100 of the plurality of optical layers 100 can include a first beam splitter. The beam splitter can include BS_1. The first beam splitter can receive a second light input. The first beam splitter can receive a third light input. The first beam splitter can output the first light input. The first beam splitter can output a third light output.

[0045] The lens 110 can include a first lens 110. Each optical layer 100 of the plurality of optical layers 100 can include a second lens 110. The lens 110 can include the second lens 110. The second lens 110 can include the lens f_2. The second lens 110 can receive the third light output. The second lens 110 can output a fourth light output. The fourth light output can form a Fourier transform of the third light output.

[0046] Each optical layer 100 of the plurality of optical layers 100 can include a third lens 110. The lens 110 can include the third lens 110. The third lens 110 can include the lens f_2. The third lens 110 can receive the fourth light output. The third lens 110 can output a fifth light output. The fifth light output can form a Fourier transform of the fourth light output.

[0047] Each optical layer 100 of the plurality of optical layers 100 can include a second beam splitter. The second beam splitter can include BS_2. The second beam splitter can receive the second light output. The second beam splitter can receive the fourth light output.

The second beam splitter can receive the fifth light output. The second beam splitter can output a fifth light output. The second beam splitter can output a sixth light output. The second beam splitter can output a seventh light output.

[0048] The fifth light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the fifth light output can be received by the second optical layer 100. The sixth light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the sixth light output can be received by the second optical layer 100. The seventh light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the seventh light output can be received by the second optical layer 100.

[0049] Each optical layer 100 of the plurality of optical layers 100 can include a fourth lens 110. The lens 110 can include the fourth lens 110. The fourth lens 110 can include the lens f_3. The fourth lens 110 can receive the seventh light output. The fourth lens 110 can output an eighth light output. The eighth light output can form a Fourier transform of the seventh light output.

[0050] Each optical layer 100 of the plurality of optical layers 100 can include a fifth lens 110. The lens 110 can include the fifth lens 110. The fifth lens 110 can include the lens f_3. The fifth lens 110 can receive the eighth light output. The fifth lens 110 can output a ninth light output. The ninth light output can form a Fourier transform of the eighth light output.

[0051] FIGS. 3A-3C illustrate systems 200. The system 200 can include a differentiable optical processor module. The system 200 can be for differentiable optical processors. The system 200 can include one or more optical transformers. The system 200 can have skip connections and non-linearities. The non-linearities can be introduced in the reference arm. The non-linearities can be introduced in the filter arm. The modules can be cascaded to form a larger model.

[0052] The system 200 shown in FIG. 3A can include an optical non-linearity. For example, the system 200 can include a saturable absorption nonlinearity. In this variation a saturable absorption layer, S, can be introduced at Fourier plane of the first f_2 lens. The function of S can be **S**(.). Then the module equation can be written as Equation 11.

$$E_{out} = \frac{1}{2}\left(\boldsymbol{F}(E_{in}\boldsymbol{T}) + \boldsymbol{F}\left(\boldsymbol{S}\left(\boldsymbol{F}(E_{in})\right)\right)\right) \tag{11}$$

[0053] The system 200 can include the plurality of optical layers 100. Each optical layer 100 of the plurality of optical layers 100 can include the first beam splitter. The first beam splitter can receive the second light input. The second light input can include $E_{in}/2$. The first beam splitter can receive the third light input. The first beam splitter can output the first light input. The first beam splitter can output the third light output.

[0054] The lens 110 can include a first lens 110. Each optical layer 100 of the plurality of optical layers 100 can include the second lens 110. The second lens 110 can receive the third light output. The second lens 110 can output the fourth light output. The fourth light output can form a Fourier transform of the third light output.

[0055] Each optical layer 100 of the plurality of optical layers 100 can include a saturable absorption layer 305. The saturable absorption layer 305 can include glass. The saturable absorption layer 305 can include a semiconductor material. The saturable absorption layer 305 can receive the fourth light output. The saturable absorption layer 305 can output the fifth light output. The fifth light output can include a non-linear transform of the fourth light output.

[0056] Each optical layer 100 of the plurality of optical layers 100 can include the third lens 110. The third lens 110 can receive the fifth light output. The third lens 110 can output the sixth light output. The sixth light output can form a Fourier transform of the fifth light output.

[0057] Each optical layer 100 of the plurality of optical layers 100 can include the second beam splitter. The second beam splitter can receive the second light output. The second beam splitter can receive the sixth light output. The second beam splitter can output the seventh light output. The seventh light output can include E_{out1}. The seventh light output can include $E_{out}/2$. The second beam splitter can output the eighth light output. The eighth light output can include E_{out2}. The eighth light output can include $E_{out}/2$.

[0058] The system 200 can be cascaded. For example, an adjacent optical layer 100 of the plurality of optical layers 100 can receive light. The seventh light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the seventh light output can be received by the second optical layer 100. The eighth light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the eighth light output can be received by the second optical layer 100.

[0059] The system 200 shown in FIG. 3B can include an optical non-linearity. For example, the system 200 can include a multimode fiber nonlinearity. In this variation, a multimode fiber, MMF, can be introduced at Fourier plane of the first f_2 lens. The function of S can be $\boldsymbol{M}(.\,)$. Then the module equation can be written as Equation 12.

$$E_{out} = \frac{1}{2}\left(\boldsymbol{F}(E_{in}\boldsymbol{T}) + \boldsymbol{F}\left(\boldsymbol{M}\big(\boldsymbol{F}(E_{in})\big)\right)\right) \tag{12}$$

[0060] The system 200 can include the plurality of optical layers 100. Each optical layer 100 of the plurality of optical layers 100 can include the first beam splitter. The first beam splitter can receive the second light input. The second light input can include $E_{in}/2$. The first beam splitter can receive the third light input. The first beam splitter can output the first light input. The first beam splitter can output the third light output.

[0061] The lens 110 can include a first lens 110. Each optical layer 100 of the plurality of optical layers 100 can include the second lens 110. The second lens 110 can receive the third light output. The second lens 110 can output the fourth light output. The fourth light output can form a Fourier transform of the third light output.

[0062] Each optical layer 100 of the plurality of optical layers 100 can include a multimode fiber (MMF) 310. The multimode fiber 310 can include an optical fiber. The multimode fiber 310 can be used to transport light signals. The multimode fiber 310 can include a multi-mode optical fiber. The multimode fiber 310 can receive the fourth light output. The multimode fiber 310 can output the fifth light output. The fifth light output can include a non-linear transform of the fourth light output.

[0063] Each optical layer 100 of the plurality of optical layers 100 can include the third lens 110. The third lens 110 can receive the fifth light output. The third lens 110 can output the sixth light output. The sixth light output can form a Fourier transform of the fifth light output.

[0064] Each optical layer 100 of the plurality of optical layers 100 can include the second beam splitter. The second beam splitter can receive the second light output. The second beam splitter can receive the sixth light output. The second beam splitter can output the seventh light output. The seventh light output can include E_{out1}. The seventh light output can include $E_{out}/2$. The second beam splitter can output the eighth light output. The eighth light output can include E_{out2}. The eighth light output can include $E_{out}/2$.

[0065] The system 200 can be cascaded. For example, an adjacent optical layer 100 of the plurality of optical layers 100 can receive light. The seventh light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the seventh light output can be received by the second optical layer 100. The eighth light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the eighth light output can be received by the second optical layer 100.

[0066] The system 200 shown in FIG. 3C can include one or more optical non-linearities. The system 200 shown in FIG. 3C can include one or more electronic non-linearities. For example, the system 200 can include an electronic non-linearity. The system 200 can include a hybrid model. In this variation, an additional 50/50 beam splitter BS_3 can be introduced after the second f_2 lens. The light reflected from BS_3 can go to the usual beam path (e.g., similar to M_2 in previous models). The light transmitted through BS_3 can be imaged on to the detector (D) after a de-magnification (e.g., using the 4f system of f_4 and f_5). The field just before D can be E_D. The intensity of the E_D can be sampled by the detector to generate the digital signal I_D. Note that I_D can be a lower dimension than the optical-model-dimension due to demagnification and sampling. Thus I_D can be thought of a feature embedding. I_D can be then fed to a low-dimensional neural network $G(.\ )$. $G(.)$ can be designed as a network with two inputs and one output. The first input can be the embedding I_D. The second input, I_{in}, can come from the digital output of the previous layer. The output, I_{out}, of the network can be written as Equation 13.

$$I_{out} = G(I_D, I_{in}) \tag{13}$$

[0067] Thus, the module shown in FIG. 3C can be a hybrid electronic and optical module with three inputs (I_{in} , $E_{in}/2$, and $E_{in}/2$) and three outputs (I_{out} , $E_{out}/2$, and $E_{out}/2$).

[0068] The system 200 can include the plurality of optical layers 100. Each optical layer 100 of the plurality of optical layers 100 can include the first beam splitter. The first beam splitter can receive the second light input. The second light input can include $E_{in}/2$. The first beam splitter can receive the third light input. The first beam splitter can output the first light input. The first beam splitter can output the third light output.

[0069] The lens 110 can include a first lens 110. Each optical layer 100 of the plurality of optical layers 100 can include the second lens 110. The second lens 110 can receive the third light output. The second lens 110 can output the fourth light output. The fourth light output can form a Fourier transform of the third light output.

[0070] Each optical layer 100 of the plurality of optical layers 100 can include the third lens 110. The third lens 110 can receive the fourth light output. The third lens 110 can output the fifth light output. The fifth light output can form a Fourier transform of the fourth light output.

[0071] Each optical layer 100 of the plurality of optical layers 100 can include the second beam splitter. The second beam splitter can include BS_3. The second beam splitter can receive the fifth light output. The second beam splitter can output the sixth light output. The second beam splitter can output the seventh light output.

[0072] Each optical layer 100 of the plurality of optical layers 100 can include a third beam splitter. The third beam splitter can include BS_2. The third beam splitter can receive the second light output. The third beam splitter can receive the seventh light output. The second beam splitter can output the eighth light output. The eighth light output can include E_{out1}. The eighth light output can include $E_{out}/2$. The third beam splitter can output the ninth light output. The ninth light output can include E_{out2}. The ninth light output can include $E_{out}/2$.

[0073] Each optical layer 100 of the plurality of optical layers 100 can include a nonlinear layer 315. The nonlinear layer 315 can receive the sixth light output. The nonlinear layer 315 can receive an electronic signal. The nonlinear layer 315 can output an electronic signal output. The electronic signal output can include I_{out}.

[0074] The system 200 can be cascaded. For example, an adjacent optical layer 100 of the plurality of optical layers 100 can receive light. The eighth light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the eighth light output can be received by the second optical layer 100. The ninth light output can be received by the adjacent layer of the plurality of optical layers 100. For example, the ninth light output can be received by the second optical layer 100. The electronic signal output can be received by the adjacent layer of the plurality of optical layers 100. For example, the electronic signal output can be received by the second optical layer 100.

[0075] The system 200 (e.g., differentiable optical processors with skip connections, optical transformer with skip connections, differentiable optical processors with electronic non-linearity, optical transformer with electronic non-linearity) can be evaluated based on a classification of MNIST digits. In this task, the input to each network can be an optical field with an MNIST digit in the phase. The amplitude of this field can be set to one. The system 200 can include the plurality of optical layers 100. The plurality of optical layers 100 can be configured as a classifier. The plurality of optical layers 100 can be configured as an image processor. The transmission coefficients can be treated as configurable parameters of the image processor. The plurality of optical layers 100 can be configured as a signal processor (e.g., general signal processor). The transmission coefficients can be treated as configurable parameters of the signal processor.

[0076] The classification task can be done all optically for the linear differentiable optical processor configuration. In this variation, the input can be sent through a cascaded set of multiple blocks (shown in FIG.2), and a detector can capture the output intensity. The detector output can have 10 regions corresponding to each of the 10 classes of the MNIST digit dataset as shown in FIG. 4. FIG. 4 illustrates detector regions. For each region, the pixel-wise summation of the intensity can be calculated. The class corresponding to the region with the maximum intensity summation can be taken as the classification output. As the parameters of this model, the phase coefficients of the optical filter in each block can be trained. An input field size and a detector size of 32 x 32 pixels and 4 cascaded blocks can be used in the simulation. The results for different filter sizes are given in Table 1.

[0077] Table 1: Results of the linear differentiable optical processor model for MNIST digit classification.

Filter size	**Train Accuracy**	**Test Accuracy**
32 x 32	0.4873	0.6125
64 x 64	0.5531	0.6438
128 x 128	0.5665	0.6719

[0078] For the differentiable optical processor with electronic non-linearity, the same optical input as the previous case for the first block can be given. The electronic input (I_{in}) of the first block can be set as a trainable parameter. For subsequent blocks, the electronic and optical outputs of the previous block can be given as inputs. From each block, the intensity of the field coming through the skip arm can be captured by a detector. In the simulation, this detector can capture a region of 4 x 4 pixels. The leakage of BS_3 to the detector path can be set as a learnable parameter. The non-linear network in each of these blocks can be a multilayer perceptron (MLP) with two layers with 128 and 16 neurons with GELU activation after each layer. In the final block, the hidden layers can have 128 and 10 neurons, respectively. The results of this model with different numbers of cascaded blocks are given in Table 2.

[0079] Table 2: Results of the differentiable optical processor with electronic non-linearity for MNIST digit classification.

No. of block	**Train Accuracy**	**Test Accuracy**
2	0.7350	0.8104
3	0.9405	0.9625
4	0.9591	0.9719

[0080] The differentiable optical processors can include a configurable imaging device. For example, the differentiable optical processors can include a configurable arbitrary imaging device. The differentiable optical processors can perform various imaging applications, such as all optical phase imaging and coherent confocal imaging. The differentiable optical processors can perform image acquisition.

[0081] The differentiable optical processors can be used as an imaging device (e.g., an imaging device with skip connections). An all-optical quantitative phase imaging task on a phase image dataset can be considered. FIGS. 5A-5C illustrate all-optical quantitative phase imaging via differentiable optical processors. The optical architecture can be built by combining a variation of multiple differentiable optical processor layers, as presented in the FIG. 5A. FIG. 5A illustrates the system 200 (e.g., optical setup). The system 200 can be for differentiable optical processors. The system 200 can include one or more optical transformers. The system 200 can include the plurality of optical layers 100. The plurality of optical layers 100 can be disposed upstream of a sample. The plurality of optical layers 100 can be disposed downstream of the sample. The plurality of optical layers 100 can be configured as an imaging device. The plurality of optical layers 100 can be configured as a sensing device (e.g., optical sensing device). The plurality of optical layers 100 can be configured as measurement device (e.g., optical measurement device).

[0082] The system 200 can include one or more detectors 505. The detector 505 can receive light output by the plurality of optical layers 100. For example, the detector 505 can receive the second light output. The detector 505 can receive light from the plurality of optical layers 100 after the light has interacted with the sample.

[0083] The architecture can have 10 transformer optical blocks, with 5 blocks in the illumination side and the other 5 in the detector side (n= 5). To adapt the original general differentiable optical processor layer to this imaging task, the skip connections between the image planes can be included. Each optical block F_i, B_i can have two learnable Fourier filters T_1, T_2 except for F_5 and B_5 blocks, which can have only one learnable filter T_1.

[0084] The learnable filters can be learned to minimize the L2 distance between reconstructed intensity and ground truth phase. Training can be conducted with 256 x 256-pixel image patches. The progressive-growing method can be adopted to learn the filters. FIG. 5B shows the output field immediately before the sample. The output field can include a learned field. FIG. 5C shows the learned filters. Row a) of the learned filters can display the amplitude of the filters in F_i. Row b) of the learned filters can display the phase of the filters in F_i. Row c) of the learned filters can display the amplitude of the filters in B_i, phase of the filters in B_i. The filters can be normalized by the maximum value.

[0085] FIGS. 6A-6C illustrate coherent confocal imaging via differentiable optical processors. FIG. 6A illustrates the system 200 (e.g., optical setup). The system 200 can be for differentiable optical processors. The system 200 can include one or more optical transformers. The system 200 can include the plurality of optical layers 100. The plurality of optical layers 100 can be disposed upstream of a sample. The plurality of optical layers 100 can be disposed downstream of the sample. The plurality of optical layers 100 can be configured as an imaging device. The plurality of optical layers 100 can be configured as a sensing device (e.g., optical sensing device). The plurality of optical layers 100 can be configured as measurement device (e.g., optical measurement device).

[0086] The differentiable optical processors can be used for coherent confocal imaging. The refractive confocal propagation can be computationally implemented. This is shown in FIG. 6A. A similar optical setup as in the previous section with a few modifications can be considered.

[0087] The performance of the differentiable optical processors to learn a particular imaging principle (e.g., coherent confocal) without having explicit information about the setup can be evaluated. Since the confocal principle may not depend on the data distribution, a general set of filters that work with any data distribution can be learned. To achieve this, the differentiable optical processors can be trained with two synthetic volumetric datasets, MNIST-3d digits and synthetic beads 3d (SynBeads-3d). MNIST-3d and SynBeads-3d can have samples with the size of 127 x 127 x 5 (number of pixels along x, y, z dimensions, Nx= 127, Ny= 127, Nz= 5). The following considerations can be made: $dx = \lambda/8$, $dy = \lambda/8$, $dz = 5\lambda$. $\lambda = 690\ nm$ can be the wavelength of the illumination source. The output of the differentiable optical processors can be the sum of the detected intensities. The differentiable optical processors can be trained to minimize the distance between the output (e.g., scalar) and the center refractive index of the middle plane of the sample. FIG. 6B shows the optical fields immediately before each plane of the volume sample after the training. The optical fields can include learned fields. The learned fields can be immediately before each z-plane of the sample volume. The amplitude is shown on the top and the phase is shown on the bottom.

[0088] To test the model, a volumetric confocal dataset (confocal-3d) with larger Nx, Ny can be created by randomly combining large 2d confocal images along the z-dimension. FIG. 6C shows the learned filters. Row a) of the learned filters can display the amplitude of the filters in F_i. Row b) of the learned filters can display the phase of the filters in F_i. Row c) of the learned filters can display the amplitude of the filters in B_i, phase of the filters in B_i). The filters can be normalized by the maximum value.

[0089] The systems and methods of the present disclosure are directed to differentiable optical processors. The differentiable optical processors can include a scalable optical architecture that can perform arbitrary linear transforms. With skip-connections, the differentiable optical processors can be efficiently trained. Skip connections can also increase the model capacity by mixing image signals with their Fourier representation. Three types of non-linearities can be introduced to the optical architecture to use the differentiable optical processors as a non-linear neural network. The differentiable optical processors can be used for vision tasks, such as classification. The differentiable optical processors can be a unified model to approximate imaging systems.

[0090] Linear differentiable optical processors can perform non-linear classifications. Differentiable optical processors without non-linear optics can linearly transform the input light field (e.g., input light) to an output light field (e.g., output light). Such optical processors can perform linear computations. Input data can be embedded in the optical field. With high-dimensional embedding, linear optical processors can perform non-linear computations.

[0091] For a two-dimensional classification problem, an input signal $\boldsymbol{z} = (z_1, z_2) \in R^2$ can be classified in to one of the two classes $\{A, B\}$. To do so, a decision boundary can be learned in R^2. If the classifier is linear, the decision boundary can be linear. Such a linear classifier can classify the so called "linearly separable data". FIG. 7A illustrates a linearly separable dataset. Data points on the left and right can belong to classes A and B, respectively. A linear classifier may not be able to classify data that is not linearly separable, as shown in FIG. 7B. FIG. 7B illustrates a linearly inseparable dataset. There is no linear decision boundary that can separate the outer ring of data from the inner circle of data. A linear differentiable optical processor can be used to classify linearly inseparable data as in FIG. 7B.

[0092] Linearly inseparable low-dimensional data can be linearly separated when projected to in to a high-dimensional space. When data is projected to a high-dimensional space through some kernel, support vector machines (SVMs) can classify them. SVMs can be linear classifiers.

[0093] The two-dimensional data points can be projected to a high-dimensional optical field by embedding them in a range of the diffraction limited points in the phase of the input field. Equation 14 shows an example mapping from the original two signal space to the phase of a high-dimensional input field $E_{in}(x, y) = A\ e^{\varphi_{in}(x,y)}$.

$$\varphi_{in}(x, y) = \begin{cases} z_1 : & 0 < x, y \leq N/2 \\ z_2 : & 0 < x, y \leq N/2 \\ 0 : & Otherwise \end{cases} \tag{14}$$

[0094] A is the constant amplitude of the field, and $\varphi(x, y)$ is the spatially varying phase of the field, where the data is embedded. Each diffraction-limited "pixel" in the input field E_{in} can be a "dimension" in the embedded signal. There can be N^2 such dimensions. $N^2/2$ of them can be used in the above example and in FIG. 8. FIG. 8 illustrates a high-dimensional projection of the two-dimensional input signals. A linear classifier can be trained using the differentiable optical processors with and/or without skip connections for each of the datasets shown in FIGS. 1A and 1B.

[0095] FIGS. 9A-9D shows classification results. Shown on the left is the visualization of original two-dimensional data sets with their learned decision boundary.

Shown on the right are the four optical filters learned by the model. FIGS. 9A and 9B illustrate classification results for a linearly separable dataset. FIGS. 9C and 9D illustrate classification results for a linearly inseparable dataset. As shown in FIG. 9C and 9A, the linear optical classifiers of the present disclosure can classify linearly inseparable data when projected to high-dimensional spaces by embedding in the phase of the input light field. While phase embeddings are shown, others may be implemented, such as embedding in the polarization of the input light field.

[0096] FIG. 9A shows classification results for a linearly separable dataset using an optical architecture without skip connections. FIG. 9B shows classification results for a linearly inseparable dataset using an optical architecture without skip connections. FIG. 9C shows classification results for a linearly separable dataset using an optical architecture with skip connections. FIG. 9D shows classification results for a linearly inseparable dataset using an optical architecture with skip connections.

[0097] FIG. 10 illustrates a method 1000 of performing optical processing. In brief summary, the method 1000 can include providing optical layers (BLOCK 1005). The method 1000 can include receiving a first light input (BLOCK 1010). The method 1000 can include outputting a first light output (BLOCK 1015). The method 1000 can include receiving a first light output (BLOCK 1020). The method 1000 can include outputting a second light output (BLOCK 1025).

[0098] The method 1000 can include providing optical layers (BLOCK 1005). For example, the method 1000 can include providing a plurality of optical layers. Each of the plurality of optical layers can include one or more optical filters. Each of the plurality of optical layers can include one or more lenses.

[0099] The method 1000 can include receiving a first light input (BLOCK 1010). The optical filter can receive the first light input. The first light input can include a first light field input. The optical filter can have a transmission coefficient. The method 1000 can include inputting the transmission coefficient for each of the plurality of optical layers to one or more machine learning models.

[0100] The method 1000 can include outputting a first light output (BLOCK 1015). The optical filter can output the first light output. The first light output can include the first light input scaled by the transmission coefficient. The first light output can include the first light input times the transmission coefficient.

[0101] The method 1000 can include receiving a first light output (BLOCK 1020). The lens can receive the first light output. The first light output can include a first light field output.

[0102] The method 1000 can include outputting a second light output (BLOCK 1025). The lens can output the second light output. The second light output can form a Fourier transform of the first light output. The second light output can include a second light field output. The method 1000 can include outputting a light field.

[0103] In some embodiments, the method 1000 can include receiving, by a detector, the second light output. The method 1000 can include classifying linearly inseparable data. For example, linear optical processors can be used for non-linear computations. The method 1000 can include performing linear transformations. A linear transformation can include a transformation that does not change the linear relationship between variables. The method 1000 can include performing nonlinear transformations. A nonlinear transformation can include a transformation that changes the linear relationship between variables. The method 1000 can include performing nonlinear computations.

[0104] Embodiments of the subject matter and the operations described in this specification can be implemented in digital electronic circuitry, or in computer software, firmware, or hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them. The subject matter described in this specification can be implemented as one or more computer programs, e.g., one or more circuits of computer program instructions, encoded on one or more computer storage media for execution by, or to control the operation of, data processing apparatus. Alternatively or in addition, the program instructions can be encoded on an artificially generated propagated signal, e.g., a machine-generated electrical, optical, or electromagnetic signal that is generated to encode information for transmission to suitable receiver apparatus for execution by a data processing apparatus. A computer storage medium can be, or be included in, a computer-readable storage device, a computer-readable storage substrate, a random or serial access memory array or device, or a combination of one or more of them. Moreover, while a computer storage medium is not a propagated signal, a computer storage medium can be a source or destination of computer program instructions encoded in an artificially generated propagated signal. The computer storage medium can also be, or be included in, one or more separate components or media (e.g., multiple CDs, disks, or other storage devices).

[0105] The operations described in this specification can be performed by a data processing apparatus on data stored on one or more computer-readable storage devices or received from other sources. The term “data processing apparatus” or “computing device” encompasses various apparatuses, devices, and machines for processing data, including by way of example a programmable processor, a computer, a system on a chip, or multiple ones, or combinations of the foregoing. The apparatus can include special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application specific integrated circuit). The apparatus can also include, in addition to hardware, code that creates an execution environment for the computer program in question, e.g., code that constitutes processor firmware, a protocol stack, a database management system, an operating system, a cross-platform runtime environment, a virtual machine, or a combination of one or more of them. The apparatus and execution environment can realize various different computing model infrastructures, such as web services, distributed computing and grid computing infrastructures.

[0106] A computer program (also known as a program, software, software application, script, or code) can be written in any form of programming language, including compiled or interpreted languages, declarative or procedural languages, and it can be deployed in any form, including as a stand-alone program or as a circuit, component, subroutine, object, or other unit suitable for use in a computing environment. A computer program may, but need not, correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or data (e.g., one or more scripts stored in a markup language document), in a single file dedicated to the program in question, or in multiple coordinated files (e.g., files that store one or more circuits, subprograms, or portions of code). A computer program can be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network.

[0107] Processors suitable for the execution of a computer program include, by way of example, microprocessors, and any one or more processors of a digital computer. A processor can receive instructions and data from a read only memory or a random access memory or both. The elements of a computer are a processor for performing actions in accordance with instructions and one or more memory devices for storing instructions and data. A computer can include, or be operatively coupled to receive data from or transfer data to, or both, one or more mass storage devices for storing data, e.g., magnetic, magneto optical disks, or optical disks. A computer need not have such devices. Moreover, a computer can be embedded in another device, e.g., a personal digital assistant (PDA), a Global Positioning System (GPS) receiver, or a portable storage device (e.g., a universal serial bus (USB) flash drive), to name just a few. Devices suitable for storing computer program instructions and data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices, e.g., EPROM, EEPROM, and flash memory devices; magnetic disks, e.g., internal hard disks or removable disks; magneto optical disks; and CD ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[0108] To provide for interaction with a user, implementations of the subject matter described in this specification can be implemented on a computer having a display device, e.g., a CRT (cathode ray tube) or LCD (liquid crystal display) monitor, for displaying information to the user and a keyboard and a pointing device, e.g., a mouse or a trackball, by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback, e.g., visual feedback, auditory feedback, or tactile feedback; and input from the user can be received in any form, including acoustic, speech, or tactile input.

[0109] The implementations described herein can be implemented in any of numerous ways including, for example, using hardware, software or a combination thereof. When implemented in software, the software code can be executed on any suitable processor or collection of processors, whether provided in a single computer or distributed among multiple computers.

[0110] Also, a computer may have one or more input and output devices. These devices can be used, among other things, to present a user interface. Examples of output devices that can be used to provide a user interface include printers or display screens for visual presentation of output and speakers or other sound generating devices for audible presentation of output. Examples of input devices that can be used for a user interface include keyboards, and pointing devices, such as mice, touch pads, and digitizing tablets. As another example, a computer may receive input information through speech recognition or in other audible format.

[0111] Such computers may be interconnected by one or more networks in any suitable form, including a local area network or a wide area network, such as an enterprise network, and intelligent network (IN) or the Internet. Such networks may be based on any suitable technology and may operate according to any suitable protocol and may include wireless networks, wired networks or fiber optic networks.

[0112] A computer employed to implement at least a portion of the functionality described herein may comprise a memory, one or more processing units (also referred to herein simply as “processors”), one or more communication interfaces, one or more display units, and one or more user input devices. The memory may comprise any computer-readable media, and may store computer instructions (also referred to herein as “processor-executable instructions”) for implementing the various functionalities described herein. The processing unit(s) may be used to execute the instructions. The communication interface(s) may be coupled to a wired or wireless network, bus, or other communication means and may therefore allow the computer to transmit communications to or receive communications from other devices. The display unit(s) may be provided, for example, to allow a user to view various information in connection with execution of the instructions. The user input device(s) may be provided, for example, to allow the user to make manual adjustments, make selections, enter data or various other information, or interact in any of a variety of manners with the processor during execution of the instructions.

[0113] The various methods or processes outlined herein may be coded as software that is executable on one or more processors that employ any one of a variety of operating systems or platforms. Additionally, such software may be written using any of a number of suitable programming languages or programming or scripting tools, and also may be compiled as executable machine language code or intermediate code that is executed on a framework or virtual machine.

[0114] In this respect, various inventive concepts may be embodied as a computer readable storage medium (or multiple computer readable storage media) (e.g., a computer memory, one or more floppy discs, compact discs, optical discs, magnetic tapes, flash memories, circuit configurations in Field Programmable Gate Arrays or other semiconductor devices, or other non-transitory medium or tangible computer storage medium) encoded with one or more programs that, when executed on one or more computers or other processors, perform methods that implement the various embodiments of the solution discussed above. The computer readable medium or media can be transportable, such that the program or programs stored thereon can be loaded onto one or more different computers or other processors to implement various aspects of the present solution as discussed above.

[0115] The terms “program” or “software” are used herein to refer to any type of computer code or set of computer-executable instructions that can be employed to program a computer or other processor to implement various aspects of embodiments as discussed above. One or more computer programs that when executed perform methods of the present solution need not reside on a single computer or processor, but may be distributed in a modular fashion amongst a number of different computers or processors to implement various aspects of the present solution.

[0116] Computer-executable instructions may be in many forms, such as program modules, executed by one or more computers or other devices. Program modules can include routines, programs, objects, components, data structures, or other components that perform particular tasks or implement particular abstract data types. The functionality of the program modules can be combined or distributed as desired in various embodiments.

[0117] Also, data structures may be stored in computer-readable media in any suitable form. For simplicity of illustration, data structures may be shown to have fields that are related through location in the data structure. Such relationships may likewise be achieved by assigning storage for the fields with locations in a computer-readable medium that convey relationship between the fields. However, any suitable mechanism may be used to establish a relationship between information in fields of a data structure, including through the use of pointers, tags or other mechanisms that establish relationship between data elements.

[0118] Any references to implementations or elements or acts of the systems and methods herein referred to in the singular can include implementations including a plurality of these elements, and any references in plural to any implementation or element or act herein can include implementations including only a single element. References in the singular or plural form are not intended to limit the presently disclosed systems or methods, their components, acts, or elements to single or plural configurations. References to any act or element being based on any information, act or element may include implementations where the act or element is based at least in part on any information, act, or element.

[0119] Any implementation disclosed herein may be combined with any other implementation, and references to “an implementation,” “some implementations,” “an alternate implementation,” “various implementations,” “one implementation” or the like are not necessarily mutually exclusive and are intended to indicate that a particular feature, structure, or characteristic described in connection with the implementation may be included in at least one implementation. Such terms as used herein are not necessarily all referring to the same implementation. Any implementation may be combined with any other implementation, inclusively or exclusively, in any manner consistent with the aspects and implementations disclosed herein.

[0120] References to “or” may be construed as inclusive so that any terms described using “or” may indicate any of a single, more than one, and all of the described terms. References to at least one of a conjunctive list of terms may be construed as an inclusive OR to indicate any of a single, more than one, and all of the described terms. For example, a reference to “at least one of ‘A’ and ‘B’” can include only ‘A’, only ‘B’, as well as both ‘A’ and ‘B’. Elements other than ‘A’ and ‘B’ can also be included.

[0121] As used herein, the singular terms “a,” “an,” and “the” may include plural referents unless the context clearly dictates otherwise. Spatial descriptions, such as “above,” “below,” “up,” “left,” “right,” “down,” “top,” “bottom,” “vertical,” “horizontal,” “side,” “higher,” “lower,” “upper,” “over,” “under,” and so forth, are indicated with respect to the orientation shown in the figures unless otherwise specified. It should be understood that the spatial descriptions used herein are for purposes of illustration only, and that practical implementations of the structures described herein can be spatially arranged in any orientation or manner, provided that the merits of embodiments of this disclosure are not deviated by such arrangement.

[0122] As used herein, the terms “approximately,” “substantially,” “substantial” and “about” are used to describe and account for small variations. When used in conjunction with an event or circumstance, the terms can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close approximation. For example, when used in conjunction with a numerical value, the terms can refer to a range of variation less than or equal to ±10% of that numerical value, such as less than or equal to ±5%, less than or equal to ±4%, less than or equal to ±3%, less than or equal to ±2%, less than or equal to ±1%, less than or equal to ±0.5%, less than or equal to ±0.1%, or less than or equal to ±0.05%. For example, two numerical values can be deemed to be “substantially” the same if a difference between the values is less than or equal to ±10% of an average of the values, such as less than or equal to ±5%, less than or equal to ±4%, less than or equal to ±3%, less than or equal to ±2%, less than or equal to ±1%, less than or equal to ±0.5%, less than or equal to ±0.1%, or less than or equal to ±0.05%.

[0123] Additionally, amounts, ratios, and other numerical values are sometimes presented herein in a range format. It is to be understood that such range format is used for convenience and brevity and should be understood flexibly to include numerical values explicitly specified as limits of a range, but also to include all individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly specified.

[0124] The systems and methods described herein may be embodied in other specific forms without departing from the characteristics thereof. The foregoing implementations are illustrative rather than limiting of the described systems and methods.

[0125] Where technical features in the drawings, detailed description or any claim are followed by reference signs, the reference signs have been included to increase the intelligibility of the drawings, detailed description, and claims. Accordingly, neither the reference signs nor their absence have any limiting effect on the scope of any claim elements.

[0126] The systems and methods described herein may be embodied in other specific forms without departing from the characteristics thereof. The foregoing implementations are illustrative rather than limiting of the described systems and methods. Scope of the systems and methods described herein is thus indicated by the appended claims, rather than the foregoing description, and changes that come within the meaning and range of equivalency of the claims are embraced therein.

[0127] While the present disclosure has been described and illustrated with reference to specific embodiments thereof, these descriptions and illustrations do not limit the present disclosure. It should be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the true spirit and scope of the present disclosure as defined by the appended claims. The illustrations may not be necessarily drawn to scale. There may be distinctions between the artistic renditions in the present disclosure and the actual apparatus due to manufacturing processes and tolerances. There may be other embodiments of the present disclosure which are not specifically illustrated. The specification and drawings are to be regarded as illustrative rather than restrictive. Modifications may be made to adapt a particular situation, material, composition of matter, method, or process to the objective, spirit and scope of the present disclosure. All such modifications are intended to be within the scope of the claims appended hereto. While the methods disclosed herein have been described with reference to particular operations performed in a particular order, it will be understood that these operations may be combined, sub-divided, or re-ordered to form an equivalent method without departing from the teachings of the present disclosure. Accordingly, unless specifically indicated herein, the order and grouping of the operations are not limitations of the present disclosure.

WHAT IS CLAIMED IS:

1. A system, comprising:

a plurality of optical layers, each optical layer of the plurality of optical layers comprising:

an optical filter having a transmission coefficient, the optical filter configured to:

receive a first light input; and

output a first light output comprising the first light input scaled by the transmission coefficient; and

a lens configured to:

receive the first light output; and

output a second light output that forms a Fourier transform of the first light output.

2. The system of claim 1, wherein the second light output is received by an adjacent layer of the plurality of optical layers.

3. The system of claim 1, wherein the lens is a first lens and each optical layer of the plurality of optical layers comprises:

a first beam splitter configured to:

receive a second light input and a third light input; and

output the first light input and a third light output;

a second lens configured to:

receive the third light output; and

output a fourth light output that forms a Fourier transform of the third light output; and

a second beam splitter configured to:

receive the second light output and the fourth light output; and

output a fifth light output and a sixth light output.

4. The system of claim 3, wherein the fifth light output and the sixth light output are received by an adjacent layer of the plurality of optical layers.

5. The system of claim 1, wherein the lens is a first lens and each optical layer of the plurality of optical layers comprises:

a first beam splitter configured to:

receive a second light input and a third light input; and

output the first light input and a third light output;

a second lens configured to:

receive the third light output; and

output a fourth light output that forms a Fourier transform of the third light output;

a third lens configured to:

receive the fourth light output; and

output a fifth light output that forms a Fourier transform of the fourth light output; and

a second beam splitter configured to:

receive the second light output and the fifth light output; and

output a sixth light output and a seventh light output.

6. The system of claim 5, wherein the sixth light output and the seventh light output are received by an adjacent layer of the plurality of optical layers.

7. The system of claim 5, wherein each optical layer of the plurality of optical layers comprises:

a fourth lens configured to:

receive the seventh light output; and

output an eighth light output that forms a Fourier transform of the seventh light output.

8. The system of claim 5, wherein each optical layer of the plurality of optical layers comprises:

a fourth lens configured to:

receive the seventh light output; and

output an eighth light output that forms a Fourier transform of the seventh light output; and a fifth lens configured to:

receive the eighth light output; and

output a ninth light output that forms a Fourier transform of the eighth light output.

9. The system of claim 1, wherein the lens is a first lens and each optical layer of the plurality of optical layers comprises:

a first beam splitter configured to:

receive a second light input and a third light input; and

output the first light input and a third light output;

a second lens configured to:

receive the third light output; and

output a fourth light output that forms a Fourier transform of the third light output;

a saturable absorption layer configured to:

receive the fourth light output; and

output a fifth light output comprising a non-linear transform of the fourth light output;

a third lens configured to:

receive the fifth light output; and

output a sixth light output that forms a Fourier transform of the fifth light output; and

a second beam splitter configured to:

receive the second light output and the sixth light output; and

output a seventh light output and an eighth light output.

10. The system of claim 1, wherein the lens is a first lens and each optical layer of the plurality of optical layers comprises:

a first beam splitter configured to:

receive a second light input and a third light input; and

output the first light input and a third light output;

a second lens configured to:

receive the third light output; and

output a fourth light output that forms a Fourier transform of the third light output;

a multimode fiber configured to:

receive the fourth light output; and

output a fifth light output comprising a non-linear transform of the fourth light output;

a third lens configured to:

receive the fifth light output; and

output a sixth light output that forms a Fourier transform of the fifth light output; and

a second beam splitter configured to:

receive the second light output and the sixth light output; and

output a seventh light output and an eighth light output.

11. The system of claim 1, wherein the lens is a first lens and each optical layer of the plurality of optical layers comprises:

a first beam splitter configured to:

receive a second light input and a third light input; and

output the first light input and a third light output;

a second lens configured to:

receive the third light output; and

output a fourth light output that forms a Fourier transform of the third light output;

a third lens configured to:

receive the fourth light output; and

output a fifth light output that forms a Fourier transform of the fourth light output;

a second beam splitter configured to:

receive the fifth light output; and

output a sixth light output and a seventh light output;

a third beam splitter configured to:

receive the second light output and the seventh light output; and

output an eighth light output and a ninth light output; and

a nonlinear layer configured to:

receive the sixth light output and an electronic signal input; and

output an electronic signal output.

12. The system of claim 1, wherein the plurality of optical layers are configured as at least one of a classifier, an image processor, or a signal processor.

13. The system of claim 1, wherein the plurality of optical layers are configured as at least one of an imaging device, an optical sensing device, or an optical measurement device.

14. The system of claim 1, comprising:

a detector configured to receive the second light output.

15. A method comprising:

providing a plurality of optical layers each comprising an optical filter and a lens;

receiving, by the optical filter, a first light input, the optical filter having a transmission coefficient;

outputting, by the optical filter, a first light output comprising the first light input scaled by the transmission coefficient;

receiving, by the lens, the first light output; and

outputting, by the lens, a second light output that forms a Fourier transform of the first light output.

16. The method of claim 15, comprising inputting the transmission coefficient for each of the plurality of optical layers to one or more machine learning models.

17. The method of claim 15, comprising outputting a light field.

18. The method of claim 15, comprising receiving, by a detector, the second light output.

19. The method of claim 15, comprising classifying linearly inseparable data.

20. The method of claim 15, comprising performing at least one of linear transformations or nonlinear transformations.

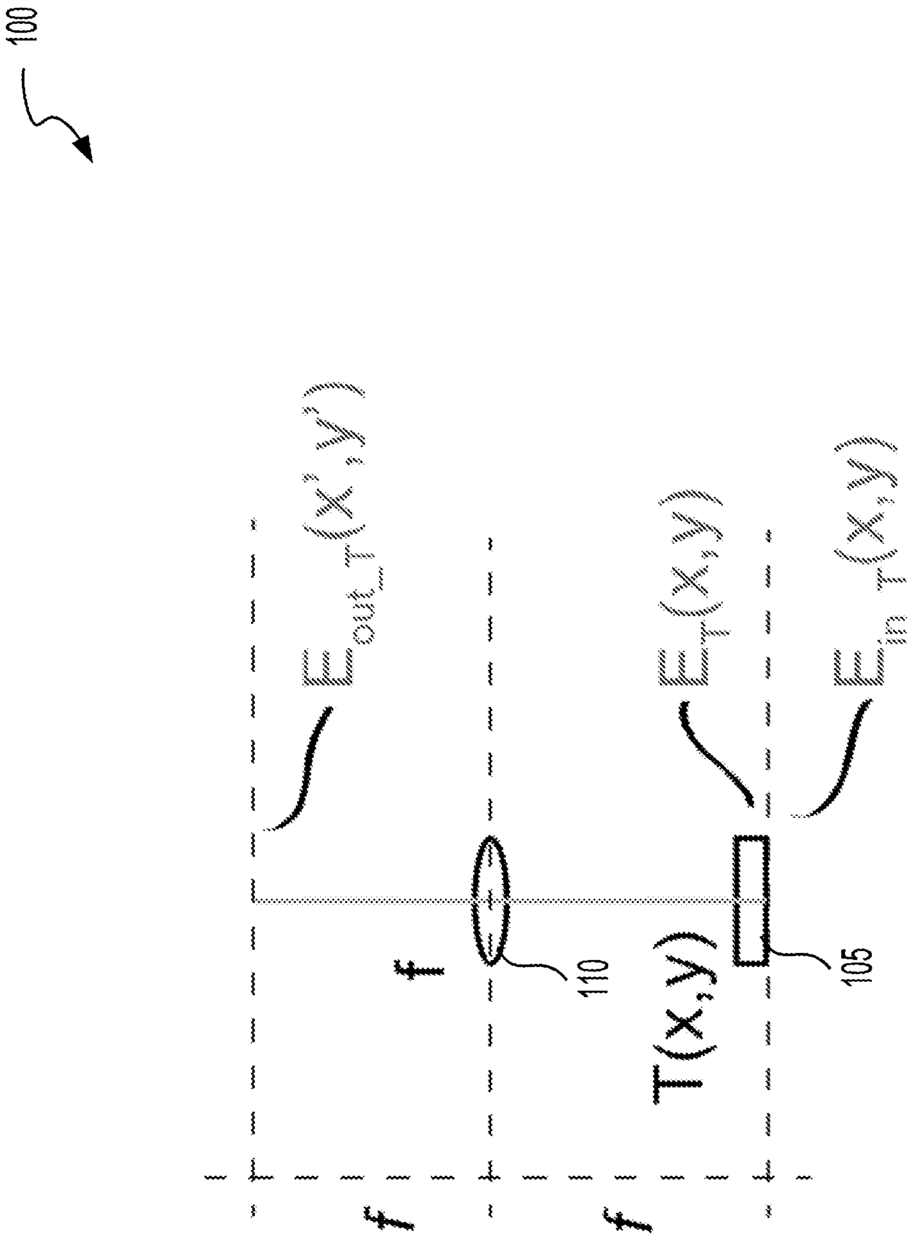

FIG. 1A

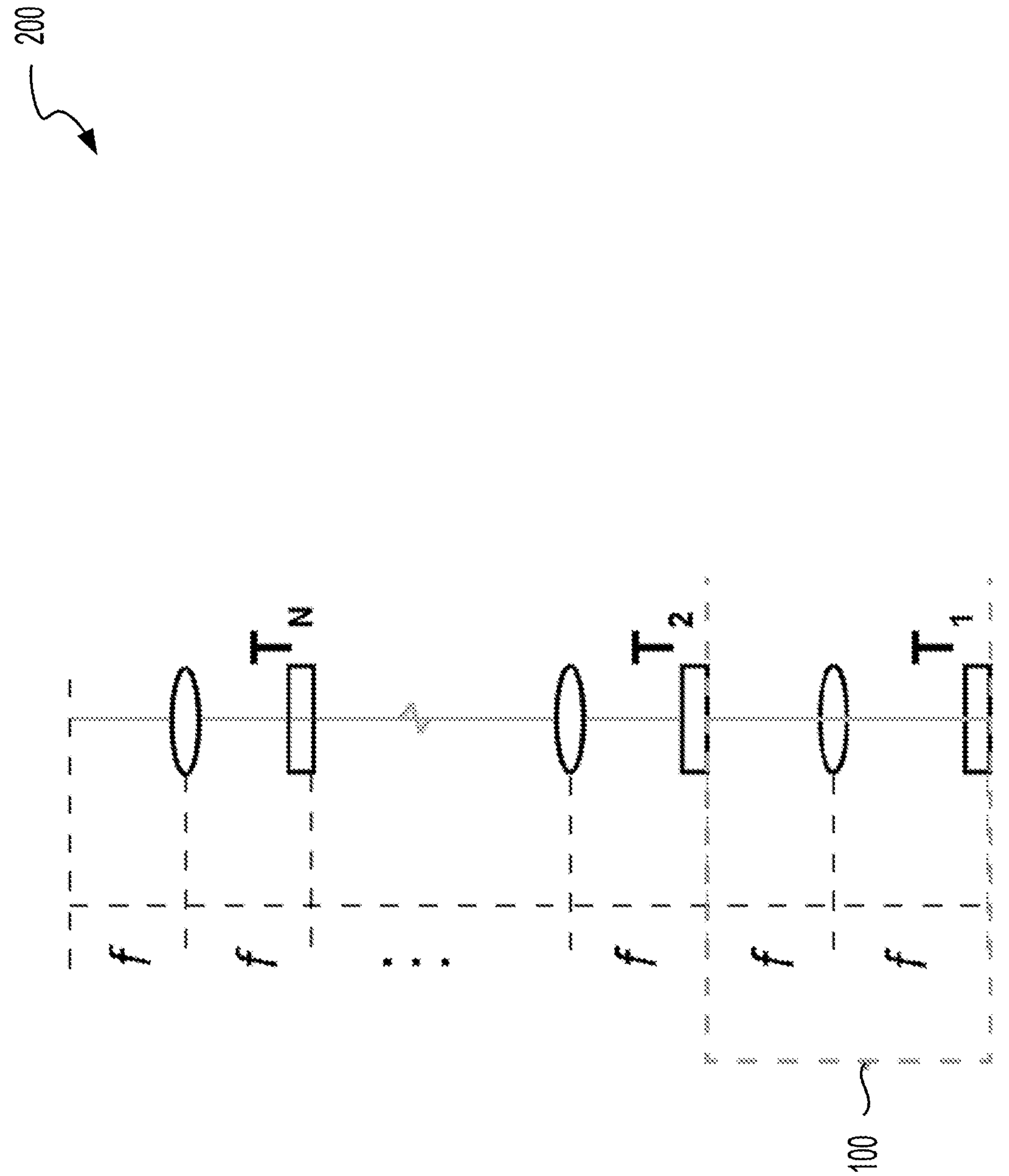

FIG. 1B

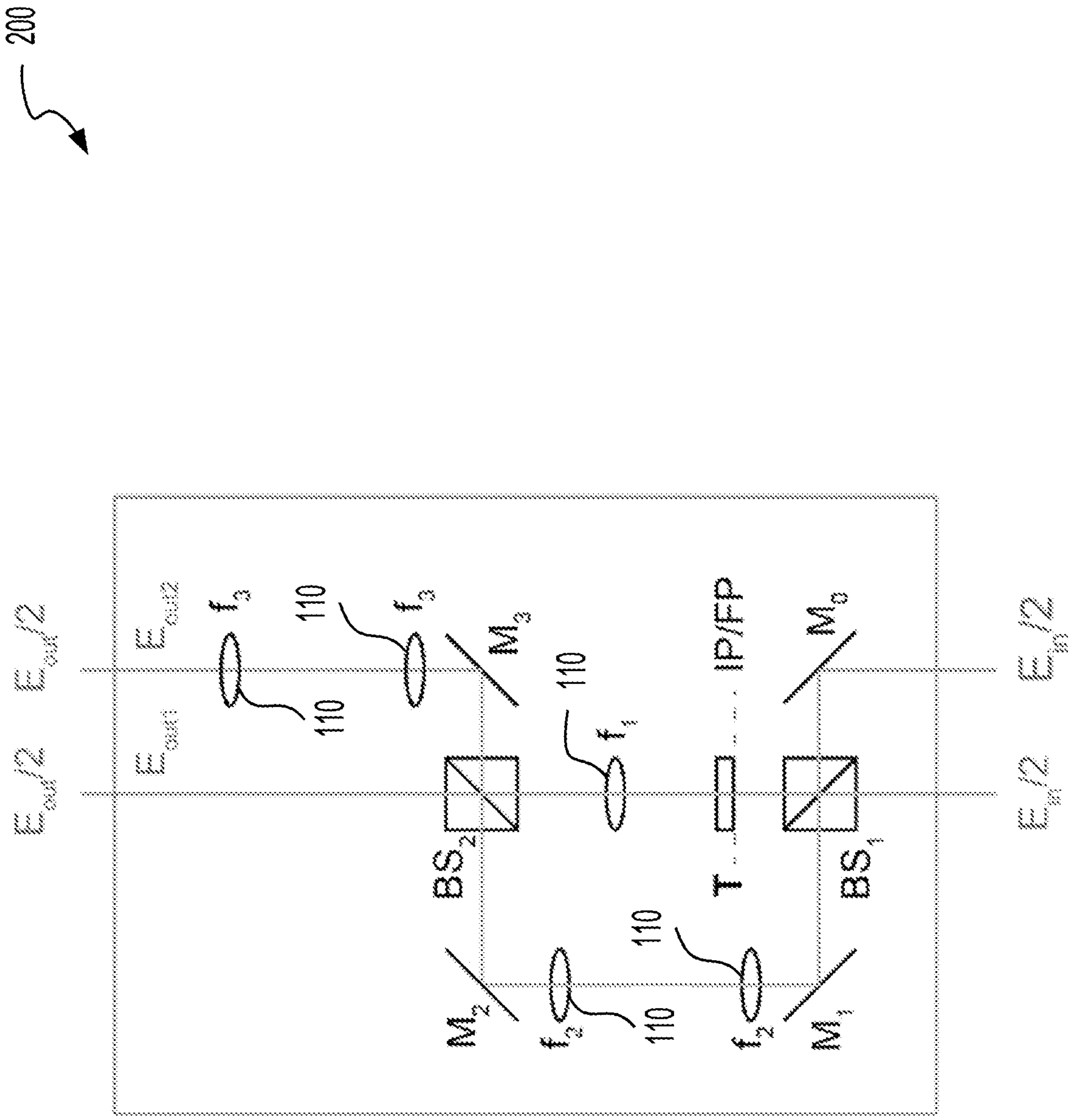
200
$E_{out}/2$
$E_{out}/2$
E_{out1}
E_{out2}
f_3
f_3
110
M_3
BS_2
M_2
f_2
f_1
T
IP/FP
M_0
BS_1
M_1
f_2
$E_{in}/2$
$E_{in}/2$

FIG. 2

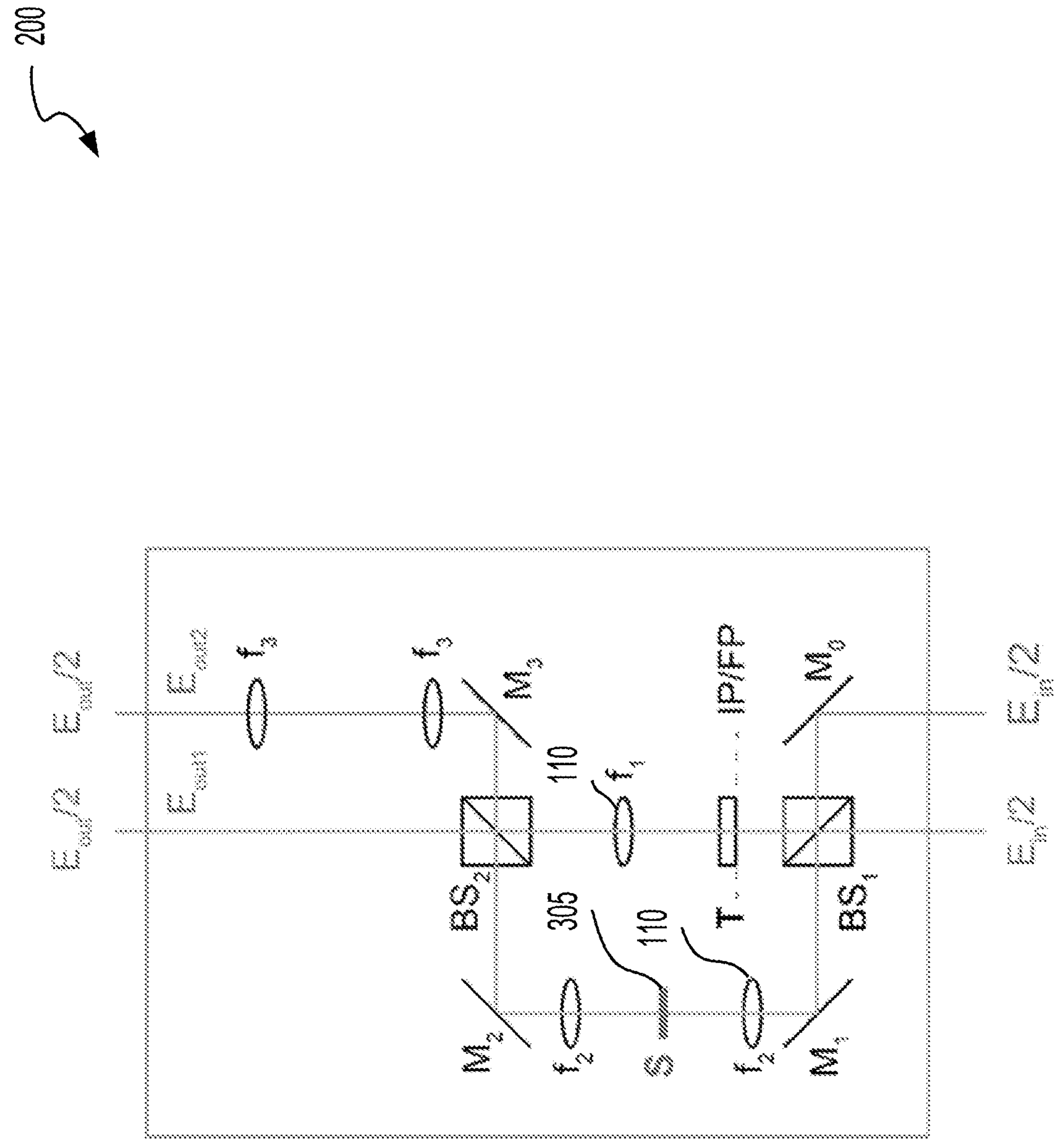
200
$E_{out}/2$
$E_{out}/2$
E_{out1}
E_{out2}
f_3
f_3
M_3
110
f_1
IP/FP
M_0
$E_{in}/2$
$E_{in}/2$
BS_2
305
110
T
BS_1
M_2
f_2
S
f_2
M_1

FIG. 3A

200

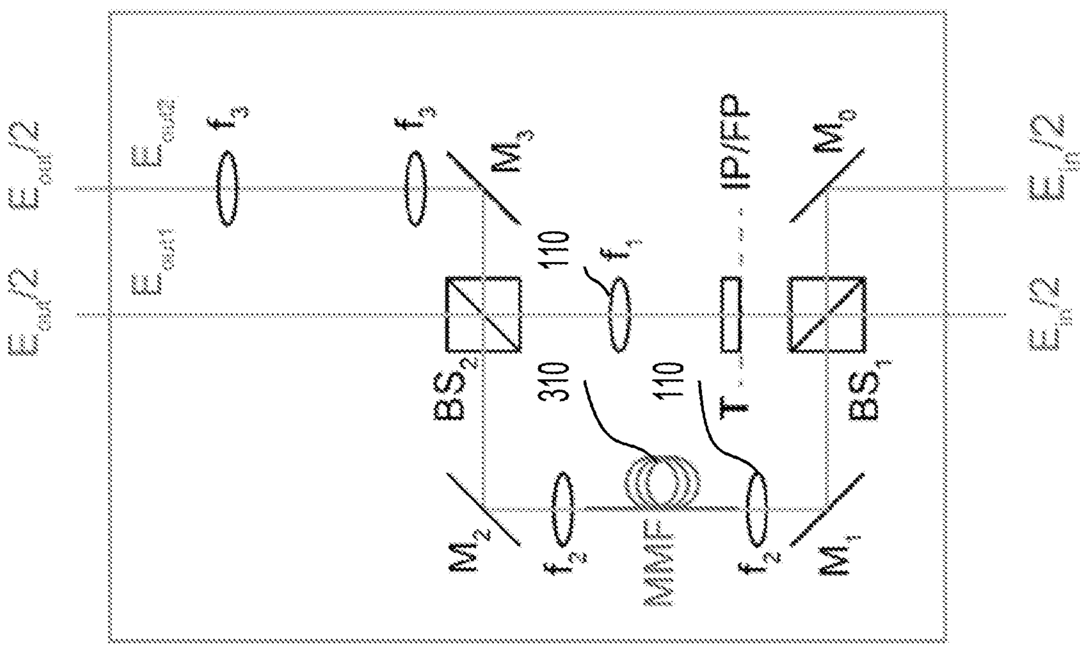
$E_{out}/2$
$E_{out}/2$
E_{out1}
E_{out2}
f_3
f_3
M_3
110
f_1
IP/FP
M_0
$E_{in}/2$
$E_{in}/2$
BS_2
310
110
T
BS_1
M_2
f_2
MMF
f_2
M_1

FIG. 3B

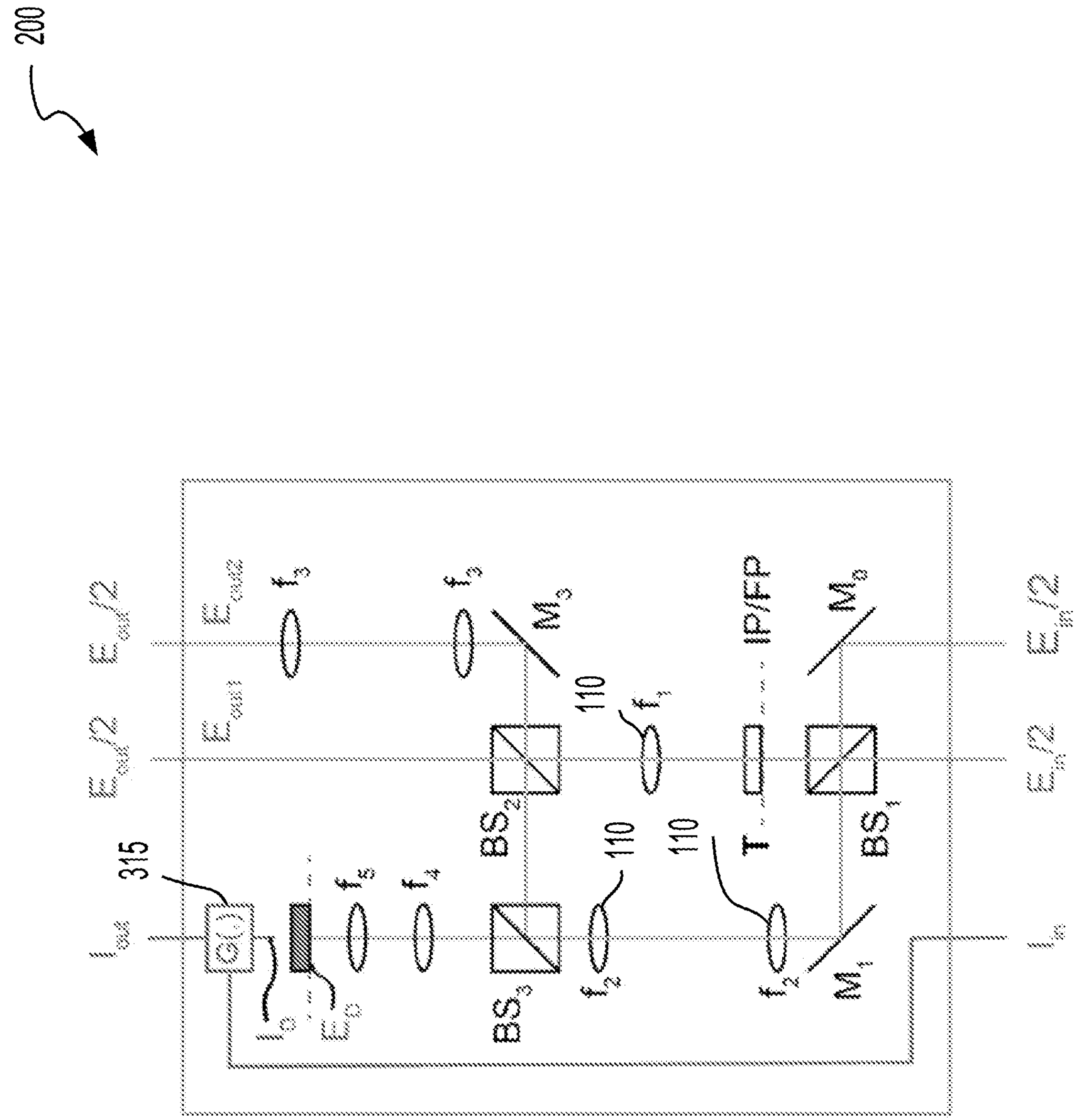
200
315
110
110
110
BS1
BS2
BS3
M0
M1
M3
f1
f2
f2
f3
f3
f4
f5
IP/FP
T
G(.)

FIG. 3C

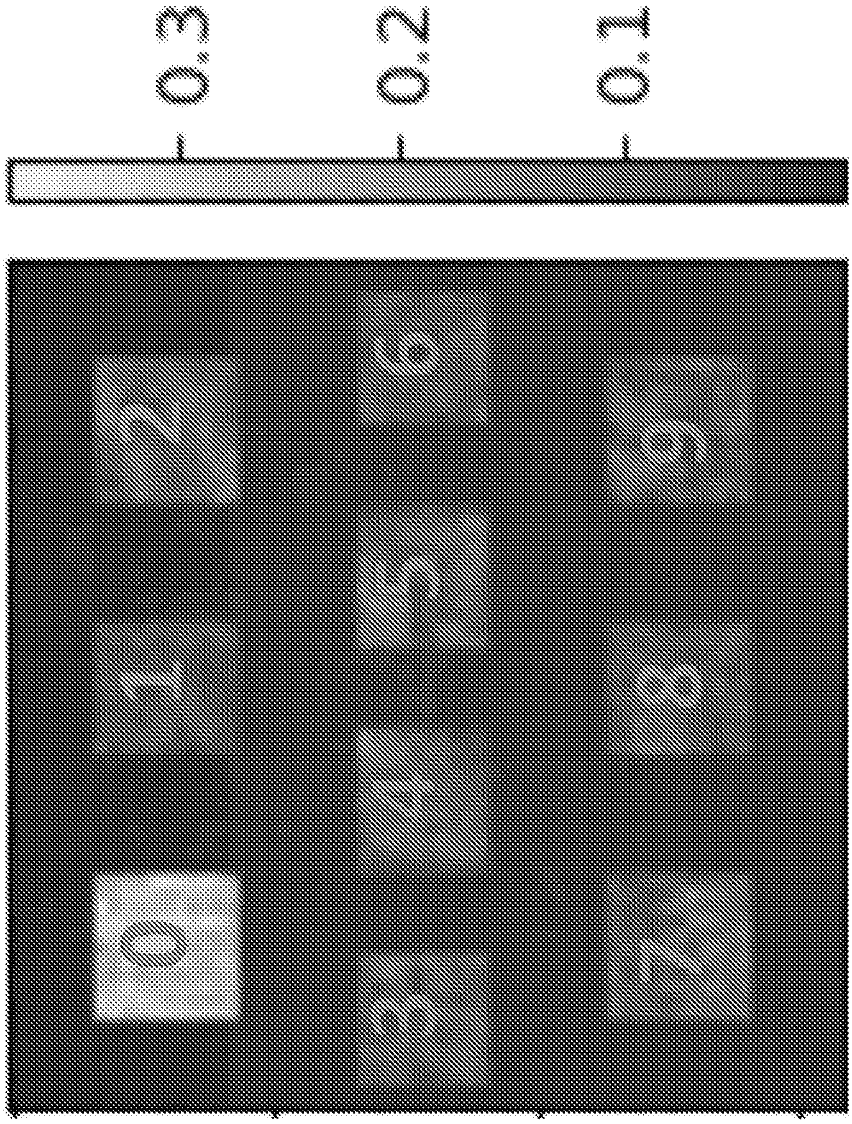

FIG. 4

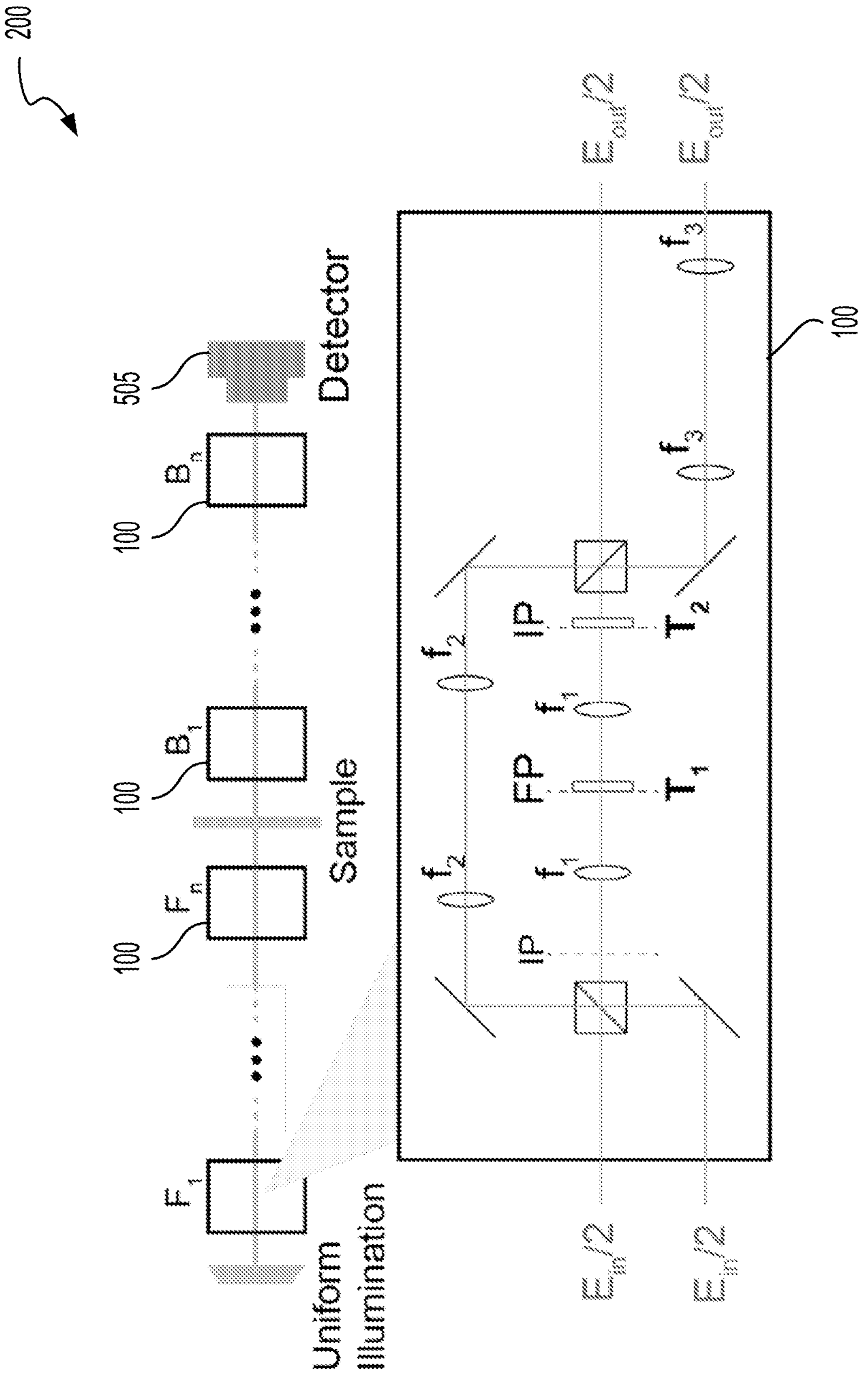
200
505
Detector
100
B_n
100
B_1
100
F_n
F_1
Sample
Uniform Illumination
IP
FP
IP
f_1
f_1
f_2
f_2
f_3
f_3
T_1
T_2
$E_{out}/2$
$E_{out}/2$
$E_{in}/2$
$E_{in}/2$
100

FIG. 5A

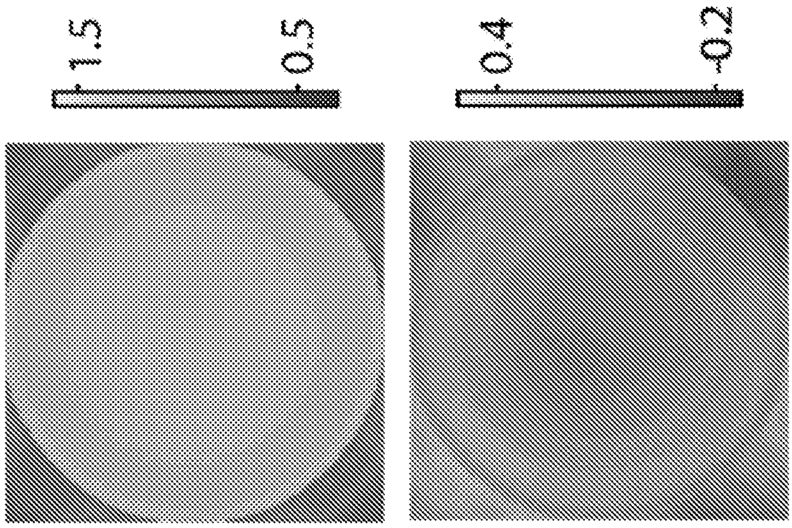

FIG. 5B

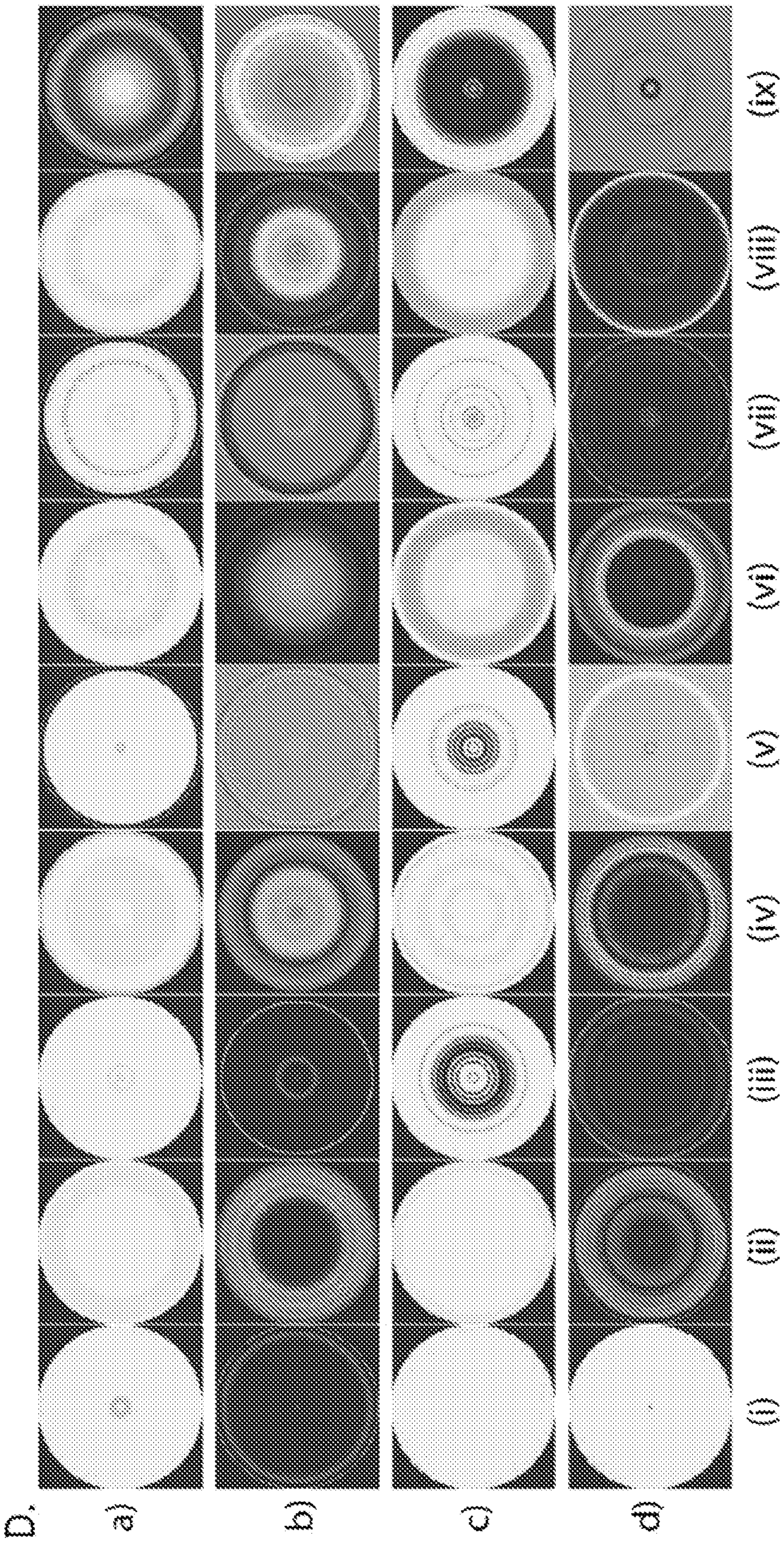

FIG. 5C

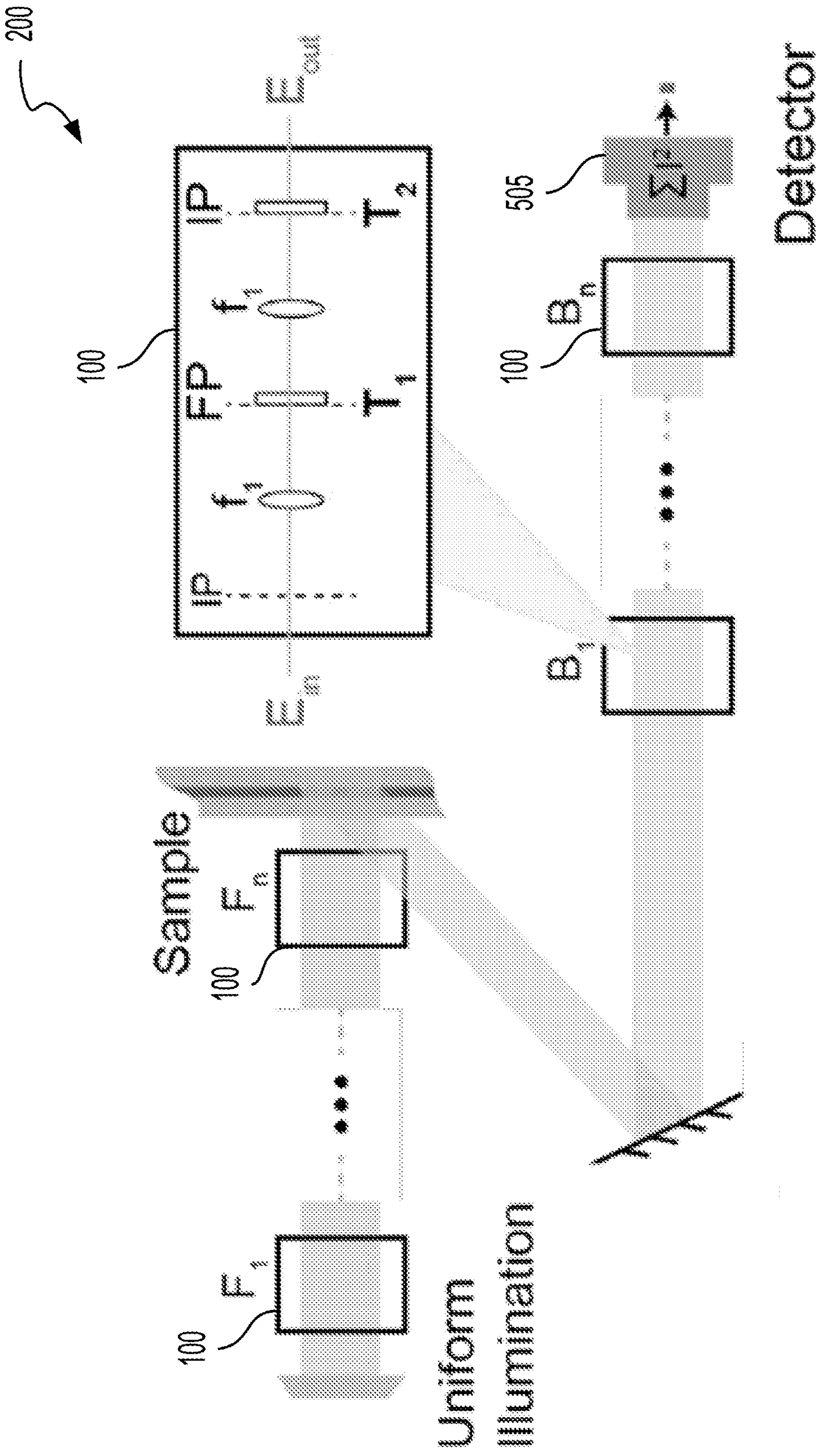
200
100
IP
FP
IP
f1
f1
T1
T2
Ein
Eout
Sample
F1
Fn
Uniform
Illumination
B1
Bn
505
Detector

FIG. 6A

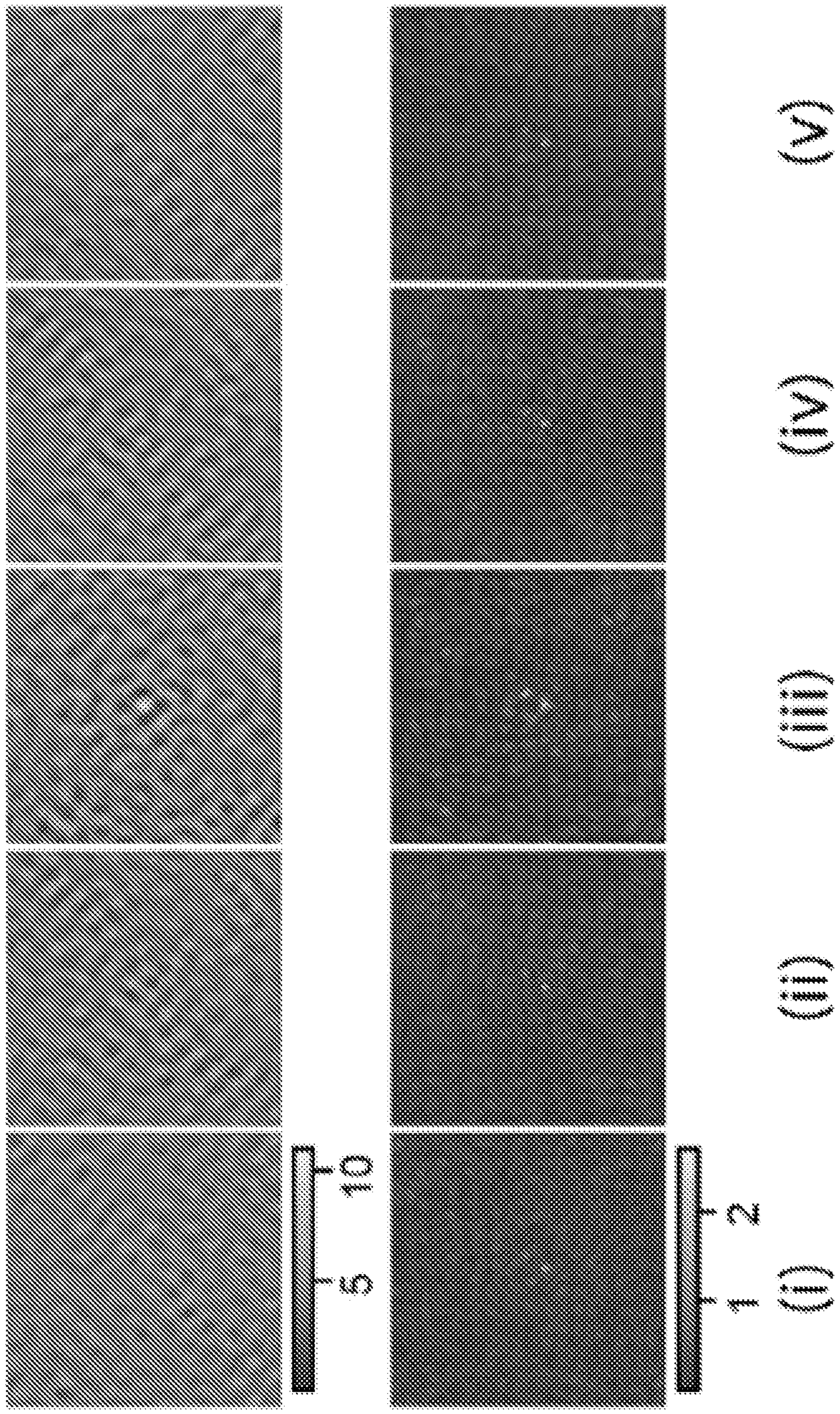

FIG. 6B

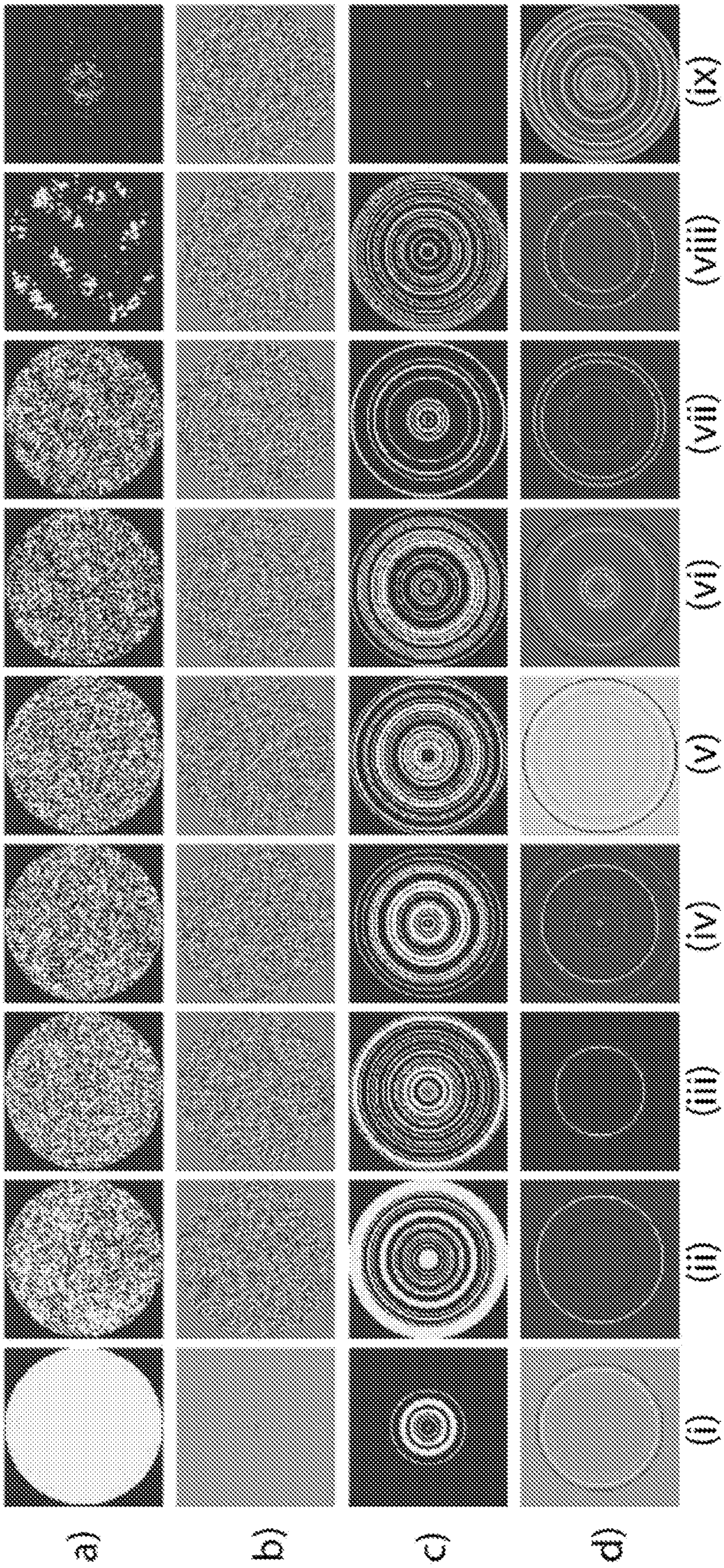

FIG. 6C

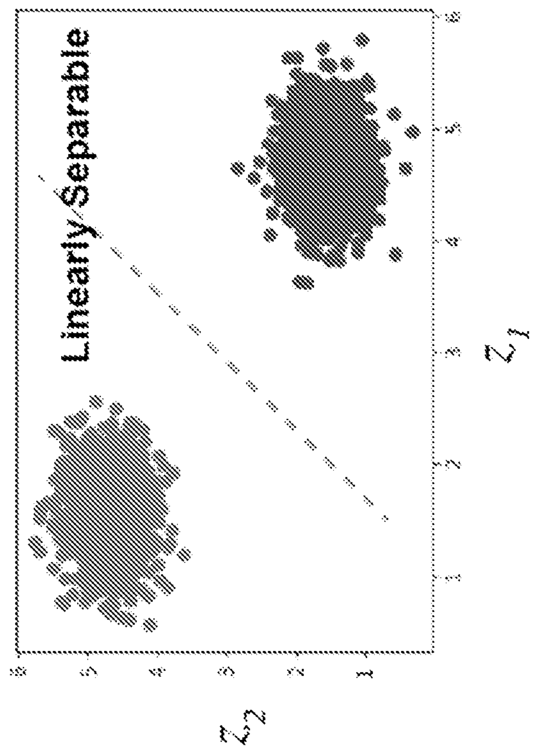

FIG. 7A

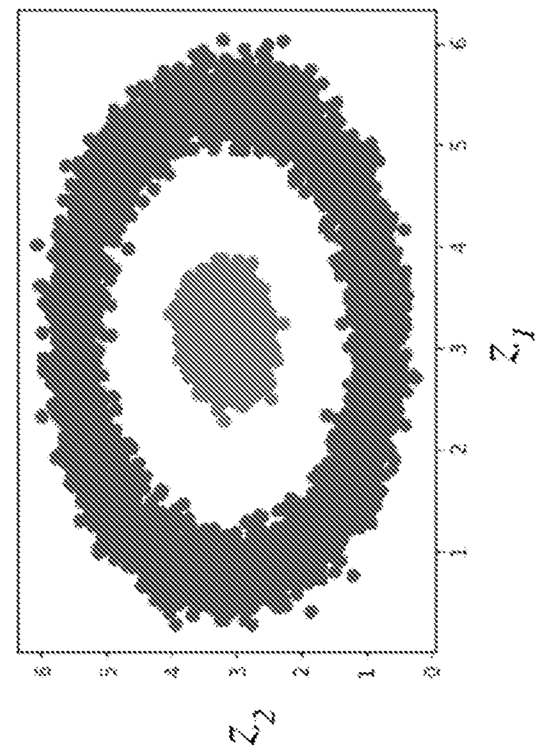

FIG. 7B

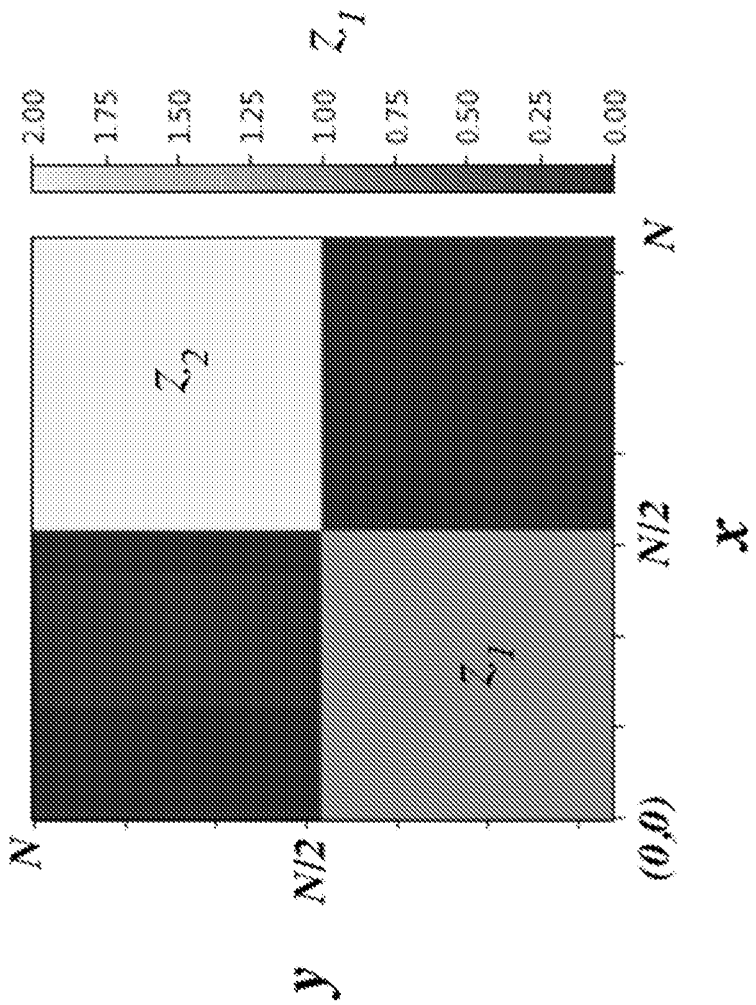

FIG. 8

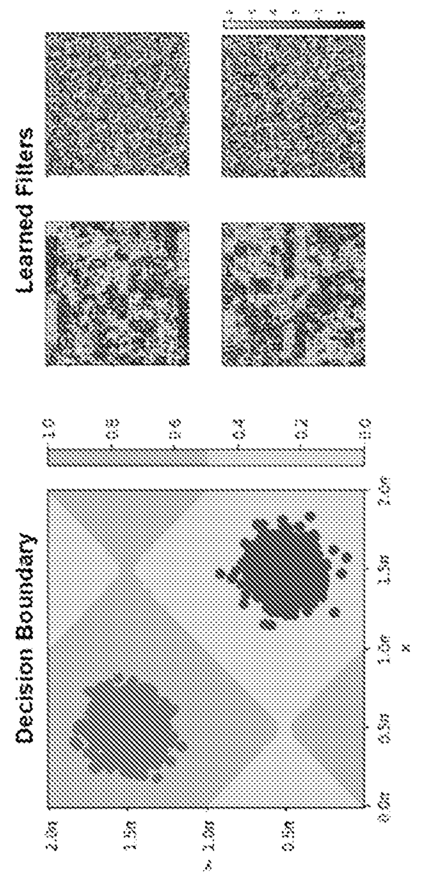

FIG. 9A

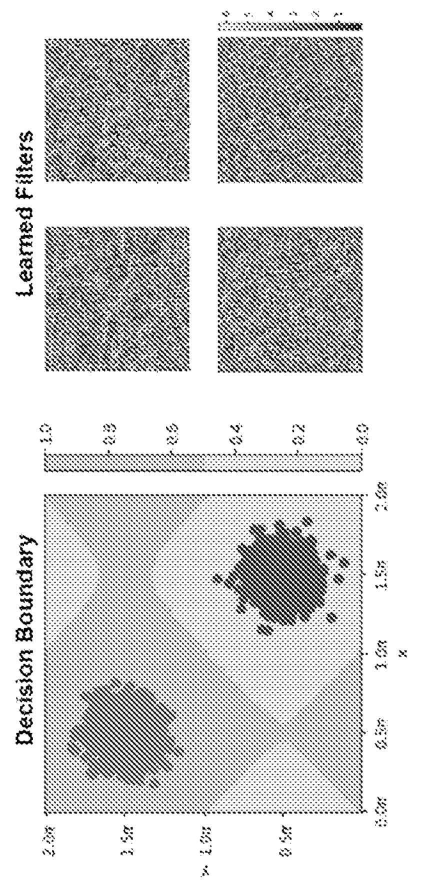

FIG. 9B

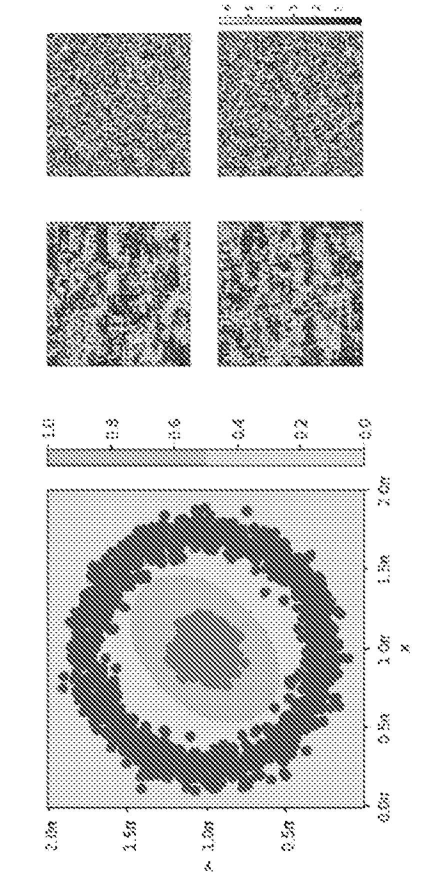

FIG. 9C

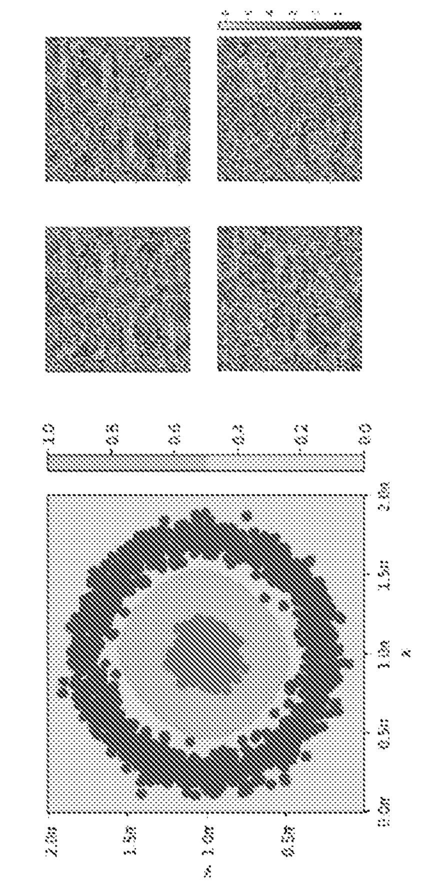

FIG. 9D

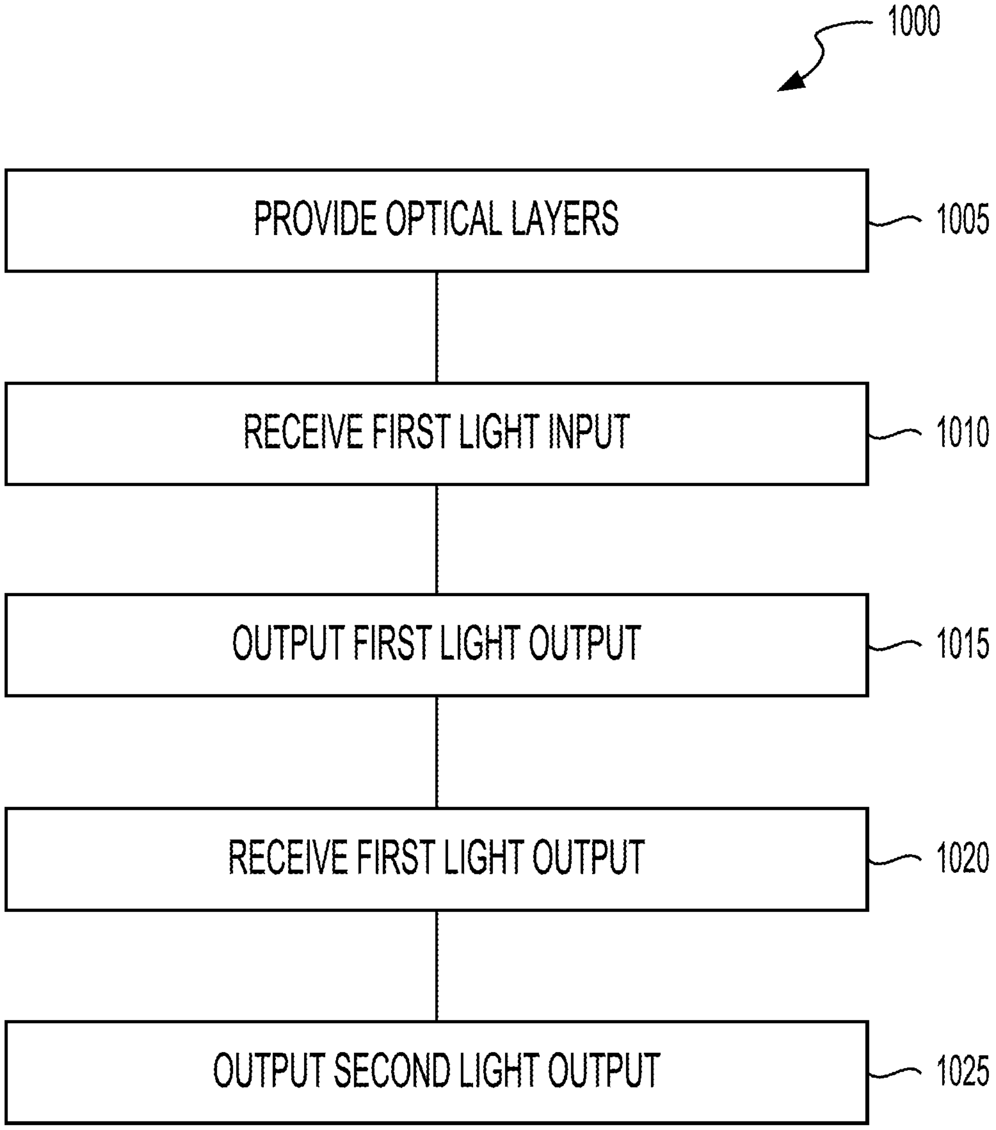
1000
PROVIDE OPTICAL LAYERS
1005
RECEIVE FIRST LIGHT INPUT
1010
OUTPUT FIRST LIGHT OUTPUT
1015
RECEIVE FIRST LIGHT OUTPUT
1020
OUTPUT SECOND LIGHT OUTPUT
1025

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2024/022258

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***G02B 27/46*** (2024.01); ***G02F 1/35*** (2024.01); ***G06F 15/80*** (2024.01); ***G06N 3/067*** (2024.01)

CPC: ***G06N 3/067; G06F 15/80; G02F 1/35; G02B 27/46;*** *G02B 6/2817; G06E 3/005*

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.
	US 11,604,978 B2 (MASSACHUSETTS INSTITUTE OF TECHNOLOGY) 14 March 2023 (14.03.2023)	
X	entire document	1, 12-18, 20
Y	entire document	2, 3, 19
	US 2021/0027154 A1 (BAR ILAN UNIVERSITY) 28 January 2021 (28.01.2021)	
Y	entire document	2
	EP 499469 A2 (SUMITOMO CEMENT CO. LTD. et al.) 19 August 1992 (19.08.1992)	
Y	entire document	3
A	entire document	4-11
	WO 2017/214507 A1 (PROGRESS INC.) 14 December 2017 (14.12.2017)	
Y	entire document	19
	US 4,959,532 A (OWECHKO) 25 September 1990 (25.09.1990)	
A	entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
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- "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	Date of mailing of the international search report
28 May 2024 (28.05.2024)	**10 June 2024 (10.06.2024)**

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US **Commissioner for Patents** **P.O. Box 1450, Alexandria, VA 22313-1450**	**MATOS** **TAINA**
Facsimile No. **571-273-8300**	Telephone No. **571-272-4300**