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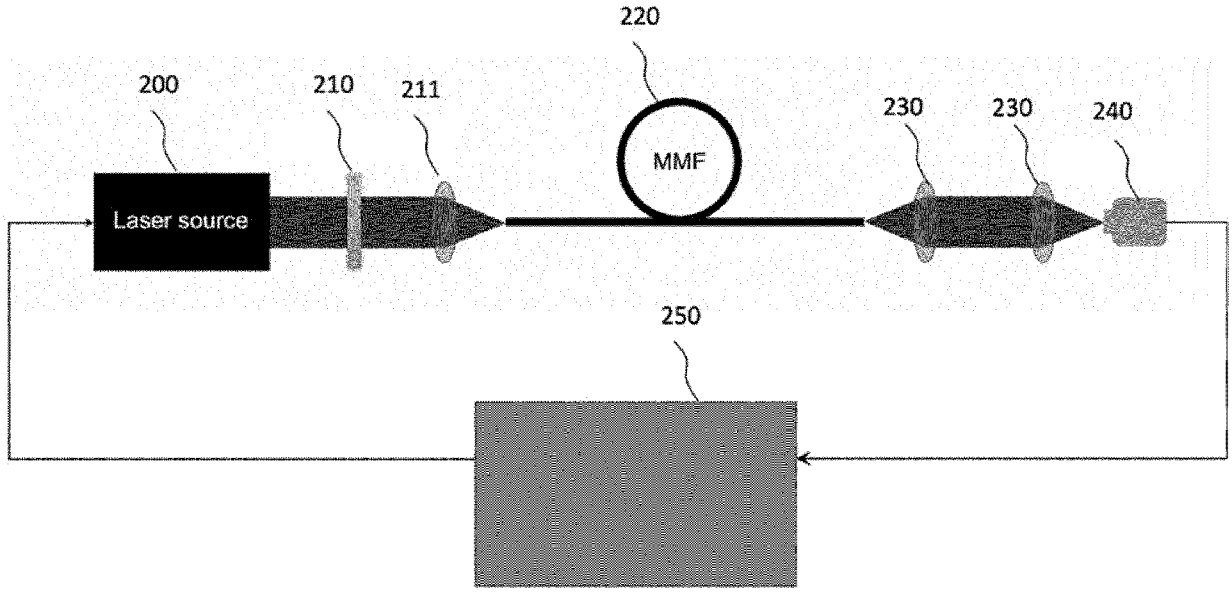


FIG. 2

(57) Abstract: A device for optical computing comprises at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) and at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220). The at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) is configured to modulate incident radiation, whereby input radiation is generated. The at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to guide the input radiation along a propagation direction. The at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to nonlinearly optically transform the input radiation propagating in the at least one waveguide, whereby output radiation that is outputted from the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320,

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WO 2022/136146 A1

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1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is optically computed.

TITLE

OPTICAL COMPUTING AND RECONFIGURING WITH SPATIOTEMPORAL NONLINEARITIES IN WAVEGUIDES

TECHNICAL FIELD

The present invention relates to systems and methods to perform optical computing by harnessing spatiotemporal nonlinear effects in optical waveguides. The general method relies on linear and nonlinear interactions of waveguide modes to realize computation engine. The optical framework allows accelerating large-scale computing for machine learning applications. Using this technique, scalable, high throughput optical information processing can be achieved by using compact active and passive components suitable for integration into existing computing platforms. The present invention furthermore relates to systems and methods to reconfigure optical computing by controlling multimode nonlinear effects in optical waveguides. The controllable optical framework allows increasing the computing performance of large-scale computing for machine learning applications. Several methods to control the high throughput optical information processing with the use of active and passive components whose size is suitable for integration into existing digital computing platforms are disclosed. In particular, the present invention relates to the field of optical computing to accelerate large scale computations in machine learning using artificial neural networks.

PRIOR ART

Optics intrinsically performs computational tasks by transforming a spatial, temporal distribution of light. Early optical computers were used to calculate linear operations such as Fourier transforms and correlations. They found applications in pattern recognition and synthetic aperture radar. However, with the advent of modern VLSI technology and dedicated algorithms (e.g. Fast Fourier Transform), digital signal processing based on silicon circuits became so fast that the analog optical computation that included the input and output electronic overhead became obsolete.

Optics has also been used for the implementation of nonlinear computations that are not based on Boolean logic, such as the optical implementation of neural networks. In principle, the dense connectivity of neural networks and their relative robustness against noise and device imperfections, renders neural networks a promising area for optical computing. Interest in optically implemented neural networks has intensified in recent years partially because the large size of databases that need to be managed stresses the capabilities of existing digital, electronic computers.

The key challenge in designing a viable optical computer (including a neural one) is to combine the linear part of the system from where the competitive edge of optics derives, with nonlinear elements and input-output interfaces while maintaining the speed and power efficiency of the optical interconnections. The prospect of an optical engine for computation is as a computational accelerator working alongside Central Processor Units (CPUs) and Graphical Processor Units (GPUs), which may be placed physically close to the edge of the communication network in order to minimize data transfer and perform the computation which would otherwise be carried out in a server farm.

To be competitive with their digital counterpart, an optical computer needs to conserve the speed and power efficiency advantages of optical data transmission that includes linear as well as nonlinear transformations. We propose an optical system interfaced and complemented with traditional digital computational units. Recently, several approaches are being investigated to perform optical computing with machine learning purposes. By combining complex, fixed mapping of optical elements with a programmable processor different optical implementation were reported [Brunner, D., Soriano, M. C., Mirasso, C. R., & Fischer, I. Parallel photonic information processing at gigabyte per second data rates using transient states. Nature Communications, 4 (1), 1-7 (2013).
Saade, A., Caltagirone, F., Carron, I., Daudet, L., Drémeau, A., Gigan, S., & Krzakala, F. Random projections through multiple optical scattering: Approximating kernels at the speed of light. IEEE International Conference on Acoustics, Speech and Signal Processing, 6215-6219 (2016).
Paudel, U., Luengo-Kovac, M., Pilawa, J., Shaw, T. J., & Valley, G. C. Classification of time-domain waveforms using a speckle-based optical reservoir computer. Optics Express, 28 (2), 1225-1237(2020)].
However, in these implementations, the non-linear transformations are not induced optically. In this disclosure, we provide methods and apparatus to modify, alter, control the

non-linear optical transformations as well as the linear transformations

Previous approaches that attempt to perform optical computing with random mapping:
Saade, A., Caltagirone, F., Carron, I., Daudet, L., Drémeau, A., Gigan, S., & Krzakala, F. Random projections through multiple optical scattering: Approximating kernels at the speed of light. IEEE International Conference on Acoustics, Speech and Signal Processing, 6215-6219 (2016).
Rafayelyan, M., Dong, J., Tan, Y., Krzakala, F., & Gigan, S. Large-Scale Optical Reservoir Computing for Spatiotemporal Chaotic Systems Prediction. Phys. Rev. X, 10 (4) 041037(2020).
Other approaches related to optical computing with multimode fibers:
Paudel, U., Luengo-Kovac, M., Pilawa, J., Shaw, T. J., & Valley, G. C. Classification of time-domain waveforms using a speckle-based optical reservoir computer. Optics Express, 28 (2), 1225-1237(2020).
Sunada, S., Kanno, K., & Uchida, A. Using multidimensional speckle dynamics for high-speed, large-scale, parallel photonic computing. Optics Express, 28 (21), 30349-30361 (2020).
These are solutions for optical computing with fixed special distributions and that involve linear transformation followed by a non-linear transformation coming from the detection of the light to electronic signal.

Optical computational techniques were shown to be able to provide high performance with low power consumption for linear operations [Spall, James, et al. "Fully reconfigurable coherent optical vector–matrix multiplication." Optics Letters 45.20 (2020): 5752-5755.]. However, one of the main challenges for an optical computer is to transform data nonlinearly without using high optical powers or electronic interfaces. Recently it was shown that [Teğin, U., Yıldırım, M., Oğuz, İ., Moser, C., & Psaltis, D. (2020), Scalable Optical Learning Operator. arXiv preprint arXiv:2012.12404.] linear and non-linear transformations can be realized with low average optical power in multimode fibers (MMF). The propagation of multiple modes inside MMFs preserves the high parallelism of free space optics, while the tight confinement and long interaction length brings about optical nonlinearities with considerably lower optical powers. The combination of linear and non-linear interactions in a multimode waveguide is capable to perform complex end-to-end learning tasks. Further background, details and explanation of this method are given herein below as well as in [Teğin, U., Moser, C., & Psaltis, D. (2020). Optical Computing with Spatiotemporal Nonlinearities. Swiss patent application CH 01656/20.].

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a device that enables a rapid optical computing. In particular it is an object of the present invention to provide a device that allows accelerating large-scale optical computing for machine learning applications.

This object is achieved with a device according to claim 1. In particular, a device for optical computing, in particular for implementing machine learning such as an artificial neural network, is provided, wherein the device comprises at least one modulator, and at least one waveguide. The at least one modulator is configured to modulate incident radiation such as electromagnetic radiation, in particular light, whereby input radiation is generated. The at least one waveguide is configured to guide the input radiation along a propagation direction. The at least one waveguide is configured to nonlinearly optically transform the input radiation propagating in the at least one waveguide, whereby output radiation that is outputted from the waveguide is optically computed.

The device is preferably configured such, that the output radiation being outputted from the waveguide is optically transformed, whereby a transformed optical signal is generated. The device preferably further comprises at least one detection device such as a camera that is configured to detect the transformed optical signal and to digitize the detected transformed optical signal, whereby digital output data is generated. The device preferably further comprises an electronic device such as a computer that is configured to receive the digital output data, and wherein the electronic device comprises a digital neural network that is configured to be trained with the digital output data.

The waveguide is preferably configured to generate a mode coupling of the input radiation propagating in the waveguide. Said mode coupling is preferably induced by nonlinear effects of the waveguide.

The waveguide is preferably configured to generate a linear mode coupling of the input radiation propagating in the waveguide. Additionally or alternatively the waveguide is preferably configured to generate a nonlinear mode coupling of the input radiation propagating in the waveguide.

The device is preferably configured to optically process information via the linear mode

coupling and/or the nonlinear mode coupling.

The waveguide is preferably configured to decompose the input radiation propagating along the propagation direction into one or more modes.

The waveguide is preferably configured to nonlinearly optically transform the input radiation being propagating in the waveguide upon a perturbation of the waveguide. The perturbation of the waveguide preferably corresponds to a bending of the waveguide and/or to one or more impurities of the waveguide.

The waveguide is preferably configured to nonlinearly optically transform the input radiation being propagating in the waveguide based on the following equation:

$$\frac{\partial A_p}{\partial z} = \underbrace{i\delta{\beta_0}^p A_p - \delta{\beta_1}^p \frac{\partial A_p}{\partial t} - i\frac{\beta_2}{2}\frac{\partial^2 A_p}{\partial t^2}}_{Propagation\ and\ Dispersion} + \underbrace{\sum_n C_{p,n} A_n}_{Linear\ Mode\ Coupling} + \underbrace{i\gamma \sum_{l,m,n} \eta_{p,l,m,n} A_l A_m {A_n}^*}_{Nonlinear\ Mode\ Coupling}$$

wherein the term A_n corresponds to the amplitude of the electric field mode n,
wherein $\eta_{p,l,m,n}$ are nonlinear coupling coefficients,
wherein $C_{p,n}$ is a linear coefficient, and
wherein β_0, β_1 and β_2 are dispersion terms. These β terms are dispersion terms that are defined by the material constituting the waveguide.

The device is preferably configured such that the computation performed by the said equation is implementable as a feed forward network. Namely, and as will be explained in greater detail below, the device is preferably configured so as to enable an optical computing that is akin to a digital feed forward network.

The waveguide preferably is an optical fiber, preferably a multimode fiber or a step index type fiber or a graded-index type fiber or a graded-index multimode fiber or a multicore fiber or a photonic bandgap fiber or a photonic crystal waveguide, an optofluidic waveguide, or a hollow-core gas fiber.

The waveguide preferably comprises or consists of at least one of: fused silica, germanium doped, ytterbium doped, erbium doped, thulium doped, holmium doped, silicon, silicon nitride, doped silicon, indium phosphide (InP), lithium niobate (LiNbO3), lithium niobite, or Gallium Arsenide (GaAs).

The waveguide is preferably configured to support multiple modes.

The waveguide preferably is a multicore waveguide, and wherein said multicore waveguide is arranged and configured such as to scale and parallelize a computing power of the device.

The cores of the multicore waveguide preferably affect each other. Each of the waveguides in the multicore fiber can be a multimode waveguide. Alternatively, the cores of the multicore waveguide preferably do not affect each other.

The waveguide is preferably written in a photonic circuit, preferably in a planar photonic circuit such as a planar light guide circuit or photonic integrated circuit. The photonic circuit preferably comprises or consists of at least one of: silicon, silicon nitride and doped silicon, Indium Phosphide (InP), lithium Niobate (LiNbO3), Gallium Arsenide (GaAs) for the multimode waveguides.

The radiation preferably is electromagnetic radiation. The radiation preferably is in the range from X-ray to millimetre wave.

The radiation preferably has a wavelength in the range of 400 nanometer to 2000 nanometer.

The radiation can be pulsed radiation and/or continuous radiation. If the radiation corresponds to continuous radiation it is furthermore preferred that it is high power continuous radiation. A continuous radiation of high power preferably has a power of 1 Kilowatt or more.

The radiation preferably has a peak intensity in the range of Watts per square centimetre to Gigawatt per centimetre. Additionally or alternatively the radiation preferably has a peak intensity of at least 1 Watt per square centimetre, preferably of at least 1 Kilowatt per square centimetre, more preferably of at least 1 Megawatt per square centimetre.

The modulator preferably is a spatial light modulator, preferably a megapixel spatial light modulator. Additionally or alternatively the modulator preferably is a temporal modulator that is configured to temporally modulate incident radiation.

The modulator preferably is a one dimensional or a two dimensional modulator.

The modulator is preferably configured to modulate a phase of incident radiation and/or an amplitude of incident radiation.

The modulator preferably is a liquid crystal modulator or a ferro electric crystal modulator. However, it should be noted that other spatial light modulators such as a DMD are likewise conceivable. The device is preferably configured to encode information such as a phase information and/or an amplitude information on radiation.

It should be noted that at least a second modulator could be present, and wherein said second modulators could be used to spatially modify the radiation being incident on the modulator being used to represent the information.

The input radiation generated by the modulator preferably comprises encoded information such as a phase information and/or an amplitude information. A phase information preferably corresponds to a phase pattern. An amplitude information preferably corresponds to an amplitude pattern.

The device preferably further comprises at least one first optical device that is arranged and configured to focus the input radiation being generated by the modulator into the waveguide. The at least one first optical device preferably corresponds to a lens or a lens assembly.

The device preferably further comprises at least one second optical device that is arranged and configured to focus the output radiation being generated by the waveguide onto at least one detection device being configured to detect the output radiation. The at least one second optical device preferably corresponds to a lens or a lens assembly.

The device preferably further comprises at least one detection device being configured to detect the output radiation and to generate at least one detection signal based on the detected output radiation.

The detection device preferably corresponds to the detection device that has been mentioned earlier, i.e. the detection device being configured to detect the transformed optical signal and to digitize the detected transformed optical signal and to generate digital output data. As such, the detection signal is preferably associated with the digital output

data.

The detection device preferably corresponds to a camera, preferably a CMOS camera or a CCD camera. Additionally or alternatively it is preferred that the detection device has a frame rate in the range of hertz to several tens of kilohertz. Additionally or alternatively it is preferred that the detection device is configured to detect the output radiation synchronized to an incidence of the radiation on the modulator.

The device preferably further comprises at least one feedback device that is configured to provide at least one feedback signal being associated with the output radiation to the modulator and/or to the input radiation and/or to a radiation source being configured to emit radiation.

The feedback device preferably is in communication with the detection device and/or with the output radiation.

The feedback device is preferably configured to affect the modulator based on the detection signal.

The feedback device is preferably configured to use the detection signal as a memory of a previous input signal to the modulator that resulted in the output radiation being associated with the said detection signal by affecting an encoding of a new input signal on the modulator.

The feedback device is preferably configured to inject a portion of the output radiation being emitted from an exit facet of the waveguide into an entrance facet of the waveguide.

In a first variant the feedback device preferably is a digital feedback device, preferably a microprocessor or an integrated circuit such as a field-programmable gate array.

In a second variant the feedback device preferably is an optical feedback device, the optical feedback device preferably being configured to provide a free-space or a waveguide-based feedback.

The device preferably further comprises at least one perturbation device that is configured to introduce perturbations on the waveguide.

The perturbation device is preferably configured to introduce mechanical perturbations. The perturbations are preferably caused by the application of a mechanical force on the waveguide, said mechanical force particularly preferably bends a radius of curvature of the waveguide.

The perturbation device preferably comprises or consists of one or more piezoelectric actuators such as an array of piezoelectric actuators.

The perturbation device is preferably configured to modify the linear coupling mode of the input radiation propagating in the waveguide.

The perturbation device is preferably configured to control a nonlinear information processing performed by the device.

The device preferably further comprises an amplification device, wherein the amplification device is configured to amplify input radiation propagating in the waveguide.

The amplification device is preferably a part of the waveguide. Alternatively, the amplification device is preferably provided separately from the waveguide such as in a cascade.

The amplification device is preferably configured to affect a distribution of the mode amplitudes of the input radiation propagating in the waveguide, preferably via gain competition.

The amplification device is preferably configured to modify the linear coupling mode and the nonlinear coupling mode of the input radiation propagating in the waveguide.

The amplification device is preferably configured to control a nonlinear information processing performed by the device.

The amplification device preferably comprises a gain medium such as a pump laser.

The amplification device preferably further comprises at least one control element that is configured to spatially and/or spectrally control an action of the amplification device, in

particular of the gain medium, on the waveguide. The control element preferably is a beam shaping element.

The amplification device preferably comprises a laser, and wherein the amplification device is arranged such, that radiation being emitted from said laser is: i) counter-propagating to the input radiation in the wave guide, or ii) propagating along the same direction as the input radiation in the waveguide, or iii) propagating along a direction being perpendicular to an extension direction of the wave guide.

The device is preferably further configured to change a spatiotemporal nonlinear propagation of the input radiation in the waveguide by controlling a cross-phase modulation between the modes of the input radiation propagating in the waveguide.

The modulator is preferably divided into two or more areas, and wherein one or more areas are configured to encode information to process by the device and the remaining areas are configured to reconfigure a mode coupling, in particular a nonlinear mode coupling and/or a linear mode coupling of the input radiation propagating in the waveguide.

The remaining areas are preferably configured to affect a cross-phase modulation between the modes of the waveguide. The remaining areas preferably correspond to pixels of a spatial light modulator.

The waveguide is preferably configured to generate a spatiotemporal nonlinear pulse propagation of the input radiation propagating in the waveguide.

The device is preferably configured to implement one or more machine learning technics using the spatiotemporal nonlinear pulse propagation in the waveguide.

The waveguide preferably constitutes and/or provides at least one optical layer of a neural network.

The waveguide preferably defines a length with respect to the propagation direction, and wherein a length section of said length represents a multi-layer feedforward connected network.

The waveguide preferably comprises 100 length sections or more, preferably 1000 lengths

sections or more.

A length of the waveguide is preferably 1 meter or more, the length of the waveguide is preferably in the order of several meter such as 5 meter.

The device is preferably configured to perform an optical computation within a time duration corresponding to the time duration required for the input radiation to propagate along a length of the waveguide at the speed of light.

The device is preferably configured to perform a nonlinear optical mapping between the radiation being incident on the modulator and the at least one detection signal.

The device is preferably further configured to combine the nonlinear optical mapping with at least one layer of a neural network, preferably at least one single-layer and/or at least one digital layer of a neural network, particularly preferably with at least one digital single-layer of neural network.

The layer of the neural network is preferably implemented in an electronic device such as a computer. The layer of the neural network is preferably trained to recognize the at least one detection signal. The layer of the neural network is preferably trained with a set of input-output pairs. Said input-output pairs preferably correspond to pairs of a particular input radiation being generated by the modulator and a particular detection signal being generated by the detection device upon detection of the output radiation corresponding to said input radiation.

The device is preferably configured such, that the detection signal is taken as a new input signal of the layer of the neural network.

An output signal being generated by the neural network is preferably computed as a weighted sum of the detection signal, the weights of the weighted sum preferably are quantities learnt by the neural network during a training phase.

The device preferably comprises or corresponds to an optical processor. The optical processor preferably is a reconfigurable optical processor.

The device can further comprises at least one optically dispersive element, wherein said

optically dispersive element is configured to optically disperse the output radiation, whereby the output radiation is spatially and spectrally optically distributed. Additionally or alternatively the device can further comprise at least one filtering element, wherein the filtering element is configured to filter one or more wavelengths.

The optically dispersive element preferably corresponds to a grating or prism or the like which is configured to spectrally disperse spatial components of the output radiation.
The optically dispersive element is preferably arranged between the waveguide and the detection device.
Additionally or alternatively, the device can comprise at least one filtering element that is configured to filter one or more wavelengths. The filtering element is preferably also arranged between the waveguide and the detection device and, if present, before or after the optically dispersive element.

The waveguide can comprise a multitude of multicore waveguides, wherein each multicore waveguide comprises a core defining an entrance facet and an exit facet, wherein the modulator comprises a multitude of pixels, and wherein an arrangement of the entrance facets of the cores matches an arrangement of the pixels of the modulator, and/or wherein the exit facets of the cores are arranged in juxtaposition.

An arrangement of the entrance facets of the cores of the multicore waveguides preferably is circular or squared.
The exit facets being arranged in juxtaposition can be said to be arranged adjacent to one another. Again in other words, the exit facets are preferably arranged so as to form a line, preferably a one dimensional line, of waveguides.

The device can further comprise at least one polarization selective optical element, wherein said polarization selective element is configured to distribute the output radiation according to its states of polarization. The polarization selective optical element preferably corresponds to a polarizing beam splitter.

The input radiation preferably is linearly or circularly polarized. The waveguide preferably is non-polarization maintaining. The linearly or circularly polarized input radiation entering the non-polarization maintaining waveguide, such as but not limited to a optical multimode fiber, preferably undergoes polarization changes due to its propagation in the waveguide. By using the polarization selective optical element the output radiation can be detected by a

detection device in a polarization resolved manner. Hence, the polarization selective optical element is preferably arranged between the waveguide and a detection device. The polarization states of the output radiation preferably correspond to s-polarized states and to p-polarized states.

The device preferably further comprises at least one radiation source being configured to emit radiation, and wherein the radiation source is arranged such, that its emitted radiation is incident on the modulator, whereby the input radiation is generated. The said radiation source preferably is a pulsed laser source.

The device preferably further comprises at least one reconfiguration arrangement, wherein the reconfiguration arrangement is configured to reconfigure a nonlinear optical transformation and preferably additionally a linear optical transformation of the input radiation propagating in the waveguide.
The expression "the reconfiguration arrangement is configured to reconfigure" is understood as the reconfiguration arrangement being configured to modify, alter or control the nonlinear optical transformation and possibly also the linear optical transformation of the input radiation propagating in the waveguide. As a result, the optical transformation performed by the waveguide is enhanced and a data processing of the device occurs with high accuracy.

In particular, the reconfiguration arrangement is configured to modify, alter or control a mode coupling, i.e. an interaction between the modes of the input radiation propagating in the waveguide. Said mode coupling or interaction is preferably induced by non-linear effects of the waveguide and is in particular generated by a cross-phase modulation and/or a four-wave-mixing process. Said mode coupling or interaction can generate an exchange of power between the modes, whereby new optical frequencies in the output radiation are generated.

The reconfiguration arrangement is preferably configured to reconfigure information to be processed by the device and/or the waveguide and/or the input radiation being propagating in the waveguide and/or the modulator and/or radiation being incident on the modulator.

The reconfiguration arrangement preferably comprises at least one pulse shaping device that is configured to shape a pulse of radiation, whereby pulsed-shaped radiation is generated. The pulse shaping device preferably is configured to alter a temporal shape

and/or a spatial shape such as a pulse length and/or a pulse amplitude and/or a pulse phase of the pulse of radiation and wherein said pulse-shaped radiation is incident on the modulator.

That is, the reconfiguration arrangement is preferably configured to reconfigure by shaping a pulse of radiation by the pulse shaping device. The pulse shaping device is preferably arranged between the radiation source and the modulator.
That is, it is preferred that the radiation of the radiation source is pulse shaped in a first step and modulated by the modulator in a second step. Again in other words it is preferred that at least part of the radiation being incident on the modulator is pulse shaped. The reconfiguration arrangement is thus preferably configured to reconfigure by using radiation being modulated in space and time.

The pulse shaping device preferably comprises at least one modulator such as a Spatial Light Modulator, and wherein said modulator is configured to shape the pulse of radiation by altering one or more parameters of the radiation of the radiation source such as the pulse length, amplitude or phase.

The reconfiguration arrangement preferably comprises the modulator, wherein the modulator is divided into two or more areas. One or more areas are configured to receive information to be processed by the device and to be irradiated with radiation, whereby the information is encoded by the irradiated radiation. One or more remaining areas of the modulator are configured to be irradiated with radiation, whereby control radiation is generated. The device is configured to preferably nonlinearly mix said control radiation with the encoded information when the control radiation and the encoded information are propagating in the waveguide.

The output radiation being outputted from the waveguide in this case corresponds to the nonlinearly mix of the control radiation with the encoded information. The information preferably corresponds to data such as images or data matrices that can be loaded on the modulator. The remaining one or more areas where the control radiation is generated can be referred to as a control area of the modulator. The modulator preferably comprises pixels, wherein pixels in the control area of the modulator can be referred to as control pixels.

The reconfiguration arrangement preferably comprises at least one preprocessing device, wherein said preprocessing device is configured to receive and preprocess information to

be processed by the device, whereby preprocessed information is generated, and wherein the preprocessing device is further configured to transfer said preprocessed information to the modulator.

To this end it is preferred that said preprocessed information is transferred to the one or more areas of the modulator in order to be encoded by the irradiated radiation and mixed with the control radiation as explained above.
The preprocessing device preferably comprises at least one preprocessing network that is configured to receive at least one preprocessing input signal, based on which it generates a preprocessing output signal. Said preprocessing input signal is preferably generated by an optimization device as will be described in greater detail below.

The reconfiguration arrangement preferably comprises at least one perturbation device that is configured to introduce perturbations on the waveguide, and wherein the perturbation device is preferably configured to non-mechanically and/or mechanically perturb the waveguide, and/or wherein the perturbation device preferably corresponds to the perturbation device as described above.

The perturbation device is preferably configured to apply a temperature change to the waveguide, and/or wherein the perturbation device comprises one or more heating elements being configured to heat the waveguide and/or one or more cooling elements being configured to cool the waveguide, the perturbation device preferably being a Peltier plate or a resistor wire, and/or wherein the perturbation device is configured to apply an electric field to the waveguide.

That is, the perturbation device can correspond to a perturbation device as described above. Additionally or alternatively, the perturbation device can be configured to perturb the waveguide in a non-mechanical manner such as by applying a temperature change and/or an electric field to the waveguide. It is preferred that the perturbation device is configured to apply a temperature change and/or an electric field at different positions along a length of the waveguide. In fact, a temperature change can be applied at different position along the length of the waveguide to perturb the incident radiation being propagating in the waveguide by changing the mode coupling strength between modes. Similarly, the perturbation device can be configured to apply a preferably altering electric field to the waveguide, which is furthermore preferably distributed along the length of the waveguide. As a consequence, the incident radiation being propagating in the waveguide is modulated.

The reconfiguration arrangement preferably comprises at least one waveguide, wherein said waveguide is configured to receive at least part of the input radiation from the modulator and to nonlinearly optically transform the input radiation propagating in the further waveguide, whereby further output radiation that is outputted from the waveguide of the reconfiguration arrangement is generated. The waveguide and the further waveguide are preferably arranged parallel to one another, and/or wherein the output radiation from the waveguide and the further output radiation from the waveguide of the reconfiguration arrangement are preferably detectable by a common detection device.

That is, the device is preferably configured to perform an optical computation with two or more waveguides, wherein said two or more waveguides share the same modulator and preferably also the same radiation source and/or the same information and/or the same detection device. In other words, a high space bandwidth product of the modulator and/or of the detection device can be divided by the smaller space bandwidth product of the two or more waveguides. Said division or sharing is preferably achieved by using two or more beam splitters or the like as they are well-known in the art. Said two or more waveguides are preferably parallelized, i.e. arranged in parallel. It should be noted that the reconfiguration arrangement can comprise two or more waveguides, which are preferably arranged in parallel such as in an array form.
The modulator preferably corresponds to a spatial modulator. The detection device preferably corresponds to a detection device as described above. It is furthermore preferred that the modulator comprises two or more areas as described above also in this case, and wherein one or more areas of the modulator are associated with the waveguides, and one or more of the remaining areas of the modulator are associated with a receipt of the information to be processed. To this end it is particularly preferred to use multiple waveguides in order to ensure that all pixels of the modulator can be used in the multiple waveguides.

The waveguide and the waveguide of the reconfiguration arrangement are preferably the same, and wherein the input radiation being propagating in the waveguide and the input radiation propagating in the waveguide of the waveguide of the reconfiguration arrangement differ from one another. Alternatively, the waveguide and the waveguide of the reconfiguration arrangement differ from one another, and wherein the input radiation being propagating in the waveguide and the input radiation propagating in the waveguide of the waveguide of the reconfiguration arrangement are the same, the waveguide and the

waveguide of the reconfiguration arrangement preferably differ in their core sizes and/or their numerical aperture.

That is, the device is configured for an optical computing being parallelized in terms of simultaneously applying different transforms on a same input radiation by coupling the same input radiation to multiple similar or dissimilar waveguides. Many different transforms on the same information to be processed by the device with different waveguides can unveil information on features of different scales.

The waveguide can form part of the reconfiguration arrangement, wherein the waveguide is a single-mode waveguide and the modulator is a temporal modulator. In other words, the high spectral- time bandwidth product of a single mode waveguide can be used to combine multiple wavelength data and control channels in a single waveguide.
The reconfiguration arrangement can comprise at least one radiation source being configured to emit radiation, wherein the device is configured such that the input radiation and said radiation are propagating simultaneously in the waveguide, and wherein a wavelength of the input radiation differs from a wavelength of the radiation.

That is, the device preferably comprises two or more radiation sources emitting radiation of different wavelengths, wherein said radiation of different wavelengths are coupled to a same waveguide simultaneously, whereby the device can be reconfigured. These different wavelengths can be such as to interact nonlinearly each other, for example based on a phenomenon such as four wave mixing. Additionally or alternatively these different wavelengths can be such as to independently do transformations on different information, in particular on different data, with effects such as self-phase modulation. Furthermore, the device can comprise at least one further modulator, wherein said further modulator is configured to modulate incident further radiation being emitted from the further radiation source, whereby further input radiation is generated. In this case the device is configured such that the input radiation and the further input radiation are propagating simultaneously in the waveguide.

The reconfiguration arrangement preferably comprises at least one modulator and at least one waveguide, wherein the modulator of the reconfiguration arrangement is arranged so as to receive the output radiation, whereby modulated input radiation is generated, and wherein the waveguide of the reconfiguration arrangement is configured to nonlinearly optically transform the modulated input radiation propagating in it, whereby further output

radiation is outputted from said waveguide.

That is, the device preferably comprises at least two waveguides and at least two modulators. These components are preferably arranged in a cascaded manner. That is, the modulator of the reconfiguration arrangement is preferably arranged after the waveguide, and the waveguide of the reconfiguration arrangement is preferably arranged after the modulator of the reconfiguration arrangement. An opposite arrangement is however likewise conceivable. Again in other words it is preferred that the device comprises consecutive waveguides between which modulators are placed. The modulator of the reconfiguration arrangement preferably comprises two or more areas as described above, and wherein one or more areas of the modulator are associated with the waveguides, and one or more of the remaining areas of the modulator are associated with a receipt of the information to be processed.

The reconfiguration arrangement preferably furthermore comprises at least one optimization device, wherein the optimization device is configured to optimize the nonlinear optical transformation and preferably additionally the linear optical transformation of the input radiation propagating in the waveguide, and wherein the optimization device is configured to provide at least one optimization signal being associated with the output radiation and/or the further output radiation to the modulator and/or to the waveguide and/or to the perturbation device and/or to the pulse-shaping device and/or to the preprocessing device and/or to the further modulator of the reconfiguration arrangement.

The optimization of the nonlinear optical transformation and preferably also of the linear optical transformation preferably corresponds to an enhancement of the cross-phase modulation and/or the four-wave mixing process mentioned above.

The optimization device is preferably configured to produce the optimization signal by applying one or more digital operations such as regression and classification and/or by applying one more machine learning algorithms such as reinforcement learning and/or by applying one or more evolutionary algorithms such as a genetic algorithm.

The optimization device is preferably configured to minimize at least one error signal being generated in response to at least one detection signal being generated by at least one detection device upon detection of the output radiation and/or the further output radiation.

This minimisation is preferably achieved by the application of the one or more digital operations. It is furthermore preferred that the minimisation is performed iteratively. For instance, an evolutionary algorithm such as the genetic algorithm can be applied by the optimization device to select a new optimisation signal that minimizes a task at the output signal such as at the output signal of a digital neural network, see further below.

The optimization device is preferably configured to produce the optimization signal based on one or more detection signals being generated by one or more detection devices that are configured to detect the output radiation and/or the further output radiation, and wherein said one or more detection signals are preferably used as a preprocessing input signal to one or more layers of a preprocessing network of the preprocessing device.

That is, it is preferred that the device comprises one or more detection devices that are configured to detect the output radiation and/or the further output radiation, whereby the detection device generates at least one detection signal. Said detection signal is then preferably sent to the optimization device, where it is used as an input signal for the generation of the optimization signal. Said optimization signal is in turn used as an input signal for the preprocessing device and/or the pulse-shaping device and/or the modulator and/or to further components of the reconfiguration arrangement.

It is particularly preferred to use two or more detection devices generating two or more detection signals, and wherein said two or more detection signals are preferably commonly used as an input signal for example to a simple one or two layer digital network of the preprocessing device.
In order to commonly use the detection signals the optimization device is preferably configured to concatenate and/or add and/or subtract, etc., the detection signals.
To this end it is furthermore preferred that the device comprises one or more polarization selective optical elements, optically dispersive elements, 4f imaging or the like, whereby the several detection signals are generated on the basis of a common output radiation and/or further output radiation.
In other words, the device allows simultaneous measurements with concatenating, adding or subtracting detection signals, whereby an accuracy of the optical computation is increased.

The optimization device is preferably in communication with the pulse shaping device, and wherein the optimization signal optimizes the shaping of the pulse of radiation such as pulse

length and/or pulse amplitude and/or pulse phase.

The optimization device is preferably in communication with the one or more remaining areas of the modulator being configured to be irradiated with radiation, wherein said one or more areas comprise pixels, and wherein the optimization signal optimizes the pixels. The pixels of the modulator are configured to change an amplitude and/or a phase of incident radiation. Consequently, the optimization device is preferably configured to optimize a phase and/or an amplitude of radiation being incident on the modulator.

The optimization device is preferably in communication with the preprocessing device, wherein the preprocessing device comprises a preprocessing network with weights, and wherein the optimization signal optimizes the weights of the preprocessing network.

The preprocessing network preferably corresponds to a convolution kernel, wherein the optimization device is preferably configured to optimize the weights of the convolution kernel such that an output objective function is minimized. In particular, the digital operations of the optimization device such as the reinforcement learning algorithm are preferably modifying the weights of the preprocessing network or of the convolution kernel to achieve higher success on the nonlinear transform's objective such as classification accuracy or regression precision.

In another aspect a system for optical computing, in particular for implementing machine learning such as implementing an artificial neural network, is provided. The system comprises at least one radiation source, at least one modulator, at least one waveguide, at least one detection device, and at least one output device. The at least one radiation source is configured to emit radiation. The at least one modulator is configured to modulate incident radiation being emitted from the at least one radiation source, whereby input radiation is generated. The at least one waveguide is configured to guide the input radiation along a propagation direction, whereby output radiation is generated. The at least one detection device is configured to detect the output radiation, to generate at least one detection signal based on the detected output radiation, and to transmit the at least detection signal to the at least one output device. The at least one output device is configured to generate at least one output signal based on the at least one detection signal and to transmit the at least one output signal to the at least one modulator. The at least one waveguide is configured to optically transform the input radiation propagating in the at least one waveguide in a nonlinear manner, whereby the output radiation is optically computed.

In other words, the system preferably comprises a device as described above as well at least one output device, at least one detection device, and at least one radiation device. Any explanations that are made with respect to the device *per se* likewise apply to the system comprising the device and vice versa.

The output device preferably is an electronic device such as a computer.

The electronic device preferably corresponds to the electronic device that has been mentioned earlier, i.e. to the electronic device being configured to receive the digital output data, and wherein the electronic device comprises a digital neural network that is configured to be trained with the digital output data.

The output device preferably comprises at least one layer of a neural network.

The output device is preferably configured to generate one or more layers of a neural network. The one or more layers preferably are digital one or more layers of a neural network. The one or more layers are preferably generated with random weights.

The output device is preferably configured to propagate the at least one detection signal through the one or more layers of the neural network, whereby at least one actual output signal is generated.

The actual output signal preferably corresponds to the output signal being transmitted from the output device to the modulator.

The output device is preferably further configured to generate at least one error signal based on the at least one actual output signal and at least one target output signal. The output device is preferably further configured to propagate the at least one error signal back to the neural network so as to update one or more weights being associated with the one or more layers of the neural network.

The output device is preferably further configured to propagate at least one further detection signal through the one or more layers of the neural network being associated with the updated one or more weights, whereby at least one further actual output signal is generated. The at least one further actual output signal preferably corresponds to the output signal

being transmitted from the output device to the modulator.

The output device is preferably configured to generate the target output signal based on at least one set of input-output pairs, and wherein said input-output pairs correspond to pairs of a particular input radiation being generated by the modulator and a particular detection signal being generated by the detection device upon detection of the output radiation corresponding to said input radiation.

In other words, the output device is preferably configured to comprise one or more layers of a neural network taking the at least one detection signal to produce an output signal. The weights of the neural network can be learnt by having one or more sets of input-output pairs. Again in other words it is preferred that the output device is configured to generate one or more layers of a neural network with random weights. To this end it is particularly preferred that the output device comprises a single layer. The detection signal being sent to the output device can be propagated preferably digitally through the preferably digital neural network to produce an output signal. Said output signal is sent from the output device to the modulator which modulates new incident radiation based on said output signal. At the same the output device can generate an error signal, which is a function of a correctly labelled output signal, herein called the actual output signal. The said one or more output signals can be preferably digitally propagated back to the neural network (so-called backpropagation in the field of the art) to update the preferably digital weights. These steps can be repeated N times, wherein N is a number of test being performed during a training phase of the neural network.

The at least one waveguide is preferably a multimode waveguide that is configured to decompose the input radiation into one or more modes, whereby the output radiation is generated as a result of non-linear coupling and preferably additionally of linear coupling between the modes.

The system preferably constitutes an opto-electronic computer.

The system preferably further comprises at least one reconfiguration arrangement as described above.

In a further aspect a method for optical computing, in particular for machine learning computations such as artificial neural network computations, is provided. The method

comprises the steps of: i) Modulating incident radiation being emitted from at least one radiation source with at least one modulator, whereby input radiation is generated; ii) Guiding the input radiation in at least one waveguide along a propagation direction, whereby output radiation is generated; iii) Detecting the output radiation and generating at least one detection signal based on the detected output radiation with at least one detection device; Transmitting the at least one detection signal to at least one output device; iv) Generating at least one output signal based on the at least one detection signal with the at least one output device; v) Transmitting the at least one output signal from the at least one output device to the at least one modulator; and vi) Modulating further radiation being emitted from the at least one radiation source with the at least one modulator based on the at least one output signal. The at least one waveguide is configured to optically transform the input radiation propagating in the at least one waveguide in a nonlinear manner, whereby the output radiation is optically computed.

That is to say, the method for optical computing preferably uses a system and/or a device as described above. Hence, any explanations with regard to the device *per se* or the system *per se* likewise apply to the method and vice versa.

The steps i) to vi) are preferably executed in this order given order. It is furthermore preferred that steps i) to vi) are repeated several times.

The method preferably further comprises the step of performing an optical computation within a time duration corresponding to the time duration required for the input radiation to propagate along a length of the waveguide at the speed of light.

The method preferably further comprises the step of performing a nonlinear optical mapping between the radiation being incident on the modulator and the at least one detection signal.

The method preferably further comprises the step of combining the nonlinear optical mapping with at least one layer of a neural network, preferably at least one single-layer and/or at least one digital layer of a neural network, particularly preferably with at least one digital single-layer of neural network being implemented in the output device.

The method preferably further comprises the step of training at least one layer of a neural network being implemented in the output device to recognize the at least one detection signal.

The method preferably further comprises the step of training at least one layer of a neural network being implemented in the output device with a set of input-output pairs, and wherein said input-output pairs correspond to pairs of a particular input radiation being generated by the modulator and a particular detection signal being generated by the detection device upon detection of the output radiation corresponding to said input radiation.

To this end it is conceivable that the detection device such as a camera detects an intensity of the output radiation as a nonlinear step. However, a holographic detection of an amplitude of the output radiation and a phase of the output radiation are conceivable as well. In this case the method for optical computing would be configured to process the complex field at the output to calculate the inputs to the output neural network.

The method preferably further comprises the step of taking the detection signal as a new input signal of at least one layer of a neural network being implemented in the output device. Said new input signal preferably corresponds to the detection signal being transmitted from the detection device to the output device upon receipt of new output radiation that has been generated from new input radiation which in turn has been generated by the modulator upon receipt of the output signal from the output device in the preceding optical computing step.

The method preferably further comprises the step of computing an output signal being generated by at least one layer of a neural network being implemented in the output device as a weighted sum of the detection signal, the weights of the weighted sum preferably are quantities learnt by the neural network during a training phase.

The method preferably further comprises the step of forming a digital neural network in the output device with at least one layer fed with the detection signal.

The method preferably further comprises the step of nonlinear optical transformation and preferably additionally a linear optical transformation of the input radiation propagating in the waveguide using a reconfiguration arrangement as described above.

Hence, in summary it can be said that the present invention is a novel optical computing framework to process information with high speed and energy efficiency. By implementing a single or few simple digital numerical decision layers after an optical layer which converts a stream of input data to a stream of output data in a highly nonlinear fashion, the obtained

opto-electronic processor performs machine learning tasks with very throughput and accuracy. Waveguide structures such as, but not limited to Multimode fibers (MMFs) exhibit waveguide properties while allowing spatial degrees of freedom. In a preferred embodiment, graded-index multimode fibers (GRIN MMFs) are presented. They have become subject of significant interest for telecommunications, imaging and nonlinear optics studies due to unique properties such as relatively low modal dispersion and periodic self-imaging. In machine learning studies, nonlinear transformation of information enables learning complex relations hidden in the data. Motivated by the recent spatiotemporal nonlinearity studies with GRIN MMFs (Teğin, U. (2018). Spatiotemporal nonlinear dynamics in graded-index multimode fibers (Master's Thesis, Bilkent University). Teğin, U., Rahmani, B., Kakkava, E., Borhani, N., Moser, C., & Psaltis, D. (2020). Controlling spatiotemporal nonlinearities in multimode fibers with deep neural networks. APL Photonics, 5(3), 030804.), we employed multimode fiber nonlinearities for optical computing and physical machine learning purposes. The present invention demonstrated a method to introduce optical nonlinearity for information processing purposes and to perform optical computing with spatiotemporal nonlinear effects.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention are described in the following with reference to the drawings, which are for the purpose of illustrating the present preferred embodiments of the invention and not for the purpose of limiting the same. In the drawings,

Fig. 1a-1b show a schematics of machine learning with neural networks according to the prior art;

Fig. 2 shows a schematics of a device and method illustrating the optical computing according to a first embodiment;

Fig. 3 shows a digital representation of the optical propagation as a digital neural network computing machine;

Fig. 4 depicts an example of measured impact of spatiotemporal nonlinear propagation on learning processes;

Fig. 5a-5d depict examples of measured machine learning tasks: Abalone dataset (a), face image dataset (b), audio digit dataset (c-d);

Fig. 6a-6b depict an example of measured machine learning task (COVID-19 dataset) and the impact of pulse peak power on learning;

Fig. 7 shows a schematics of a device and method illustrating the optical computing

according to another embodiment with digital feedback;

Fig. 8 shows a schematics of a device and method illustrating the optical computing according to another embodiment with optical feedback;

Fig. 9 shows a schematics of a device and method illustrating the optical computing according to another embodiment with mechanical control;

Fig. 10 shows a schematics of a device and method illustrating the optical computing according to another embodiment with optical control;

Fig. 11 shows a schematics of a device and method illustrating the optical computing according to another embodiment with a multicore fiber;

Fig. 12 shows a schematics of a device and method illustrating the optical computing according to another embodiment with a multimode waveguide;

Fig. 13 shows a schematics of a device and method illustrating the optical computing according to another embodiment with a multimode waveguide on a chip;

Fig. 14 shows a schematics of a device and method illustrating the optical computing according to another embodiment with a digital control;

Fig. 15 shows a schematics of a device and a method illustrating the optical computing according to another embodiment reconfigurable by light;

Fig. 16 shows a schematics of a device and a method illustrating the optical computing according to another embodiment reconfigurable by temperature;

Fig. 17 shows a schematics of a device and a method illustrating the optical computing according to another embodiment with multiple waveguides;

Fig. 18 shows a schematics of a device and a method illustrating the optical computing according to another embodiment reconfigurable by multiple wavelength;

Fig. 19 shows a schematics of a device and a method illustrating the optical computing according to another embodiment with spatially and temporally resolved acquisition;

Fig. 20 shows a schematics of a device and a method illustrating the optical computing according to another embodiment reconfigurable with polarization resolved acquisition;

Fig. 21 shows a schematics of a device and a method illustrating the optical computing according to another embodiment reconfigurable with electric field;

Fig. 22 shows a schematics of a device and a method illustrating the optical computing according to another embodiment reconfigurable in a cascaded manner.

DESCRIPTION OF PREFERRED EMBODIMENTS

As described above, the invention presents systems and methods to optically process information using spatiotemporal nonlinear pulse propagation in waveguides to implement machine learning techniques. A reconfigurable optical processor is presented that combines a fixed or reconfigurable nonlinear optical mapping between the input data loaded on a modulator such as a spatial light modulators (SLM) and a digital output consisting of a one or two dimensional optical detector such as a CMOS camera or CCD camera with a digital single-layer neural network (decision layer) implemented in a computer and trained to recognize the output recorded on the said camera using a large data set of input-output pairs. This optical computing invention performs as powerful as its digital counterparts for different tasks including regression and classification.

The invention furthermore presents systems and methods to control and process optical information using various techniques in waveguides such as but not limited to optical fibers, integrated planar circuit waveguide (PIC) to implement machine learning tasks. A reconfigurable optical processor is presented that uses light to control the light that carries information in the waveguide and methods that affect directly the waveguide properties via temperature, strain, electric, magnetic, acoustic means. These control knobs essentially reconfigure the optical computing system and allow finding optimized solutions, via an appropriate digital algorithm, such as Reinforcement learning for different machine learning tasks including regression and classification.

The solution proposed herein is the combination of the linear and nonlinear parts of the optical system in a shared volume confined in a waveguide such as, but not limited to, a multimode fiber (MMF), step index type or graded-index type (GRIN) or multicore fiber. The principal advantage of this approach is the combination of the 3D connectivity of optics with the long interaction length and lateral confinement afforded by the waveguide which makes it possible to realize optical nonlinearities at relatively low power. By the term optics and waveguide, we mean an electromagnetic radiation in the range from X-ray to millimeter wave which can be sent into a waveguide structure that supports multiple modes and mutual non-linear interaction due to an intense electromagnetic field generated by a pulses light source. At the same time, the large number of spatial modes that can be compactly supported in a waveguide maintains the traditional high parallelism feature of optics, while maintaining a compact form factor. Finally, with the availability of megapixel spatial light modulators (SLMs) and cameras, the 2D input and output interfaces to the MMF can sustain a large information processing throughput. In the invention, a spatial light modulator is any one dimensional or two-dimensional device that modifies the phase and or the amplitude of

the light. A preferred embodiment is a two-dimensional SLM with phase modulation such as, but not limited to a liquid crystal modulator, a ferro electric crystal modulator. This is explained in more detail with reference to the figures.

The following is a description of optical computing methods and systems with spatiotemporal waveguide nonlinearities. The illustrated examples are used to explain the invention. FIG 1A. illustrates a well-known prior art neural network. The digital inputs 100 are fed into nodes 110 forming multiple hidden layers. The connections between nodes have weights (numbers) which are learned during the training phase. The output of each node has a nonlinear function such as sigmoid or a so-called RelU function. The output layer 120 is the result of the neural network. Deep neural network is neural network with many hidden layers and connections. For solving complex problems, it is daunting problem to train neural networks with more than 20 layers and tens of millions of weights. When the weights of the neural network are fixed randomly in advance (without learning) and only the weights of the last layer is learned, the computation takes much less time. This type of neural network is called Extreme Learning Machines (ELM) and the network is called often a reservoir. The performance is not as good as that of a fully trained neural network. When there is feedback in a fixed (and randomly chosen) weight reservoir, the system is called a reservoir computing. This type is often used with time series. FIG 1B illustrate reservoir computing with digital inputs 130, nodes 140 and a digital output 150.

FIG 2 depicts the outline of the general optical computing method. The digital information is first loaded from a computer (not shown) onto the pixels (2D or 1D) of the SLM (211). In a preferred embodiment, the SLM is a phase SLM. In another embodiment the SLM is an amplitude SLM or both Phase and Amplitude SLM. A laser light source (200), preferability a pulsed optical source having a high peak intensity in the range from several Watts per square centimeter to approximately Megawatts per square centimeter, illuminates the said SLM in order to encode the phase or amplitude information of the SLM onto the optical field of the said laser light source. The encoded information on the pulse light beam is then focused by a lens assembly (211) on the proximal side of a multimode waveguide (220). As is well known in the literature, the number of modes M in a waveguide, such as a step index fiber can be approximated by the formula $M = \frac{V^2}{2}$, where V is the V-number of the fiber defined as $V = \frac{\pi}{\lambda} dNA$, where d is the fiber core diameter, NA, the numerical aperture of the fiber and λ, the wavelength of the light in vacuum. For example, a pulsed light source with a center wavelength of 1 μm , a fiber with diameter 500 μm with a numerical aperture of

0.5 gives 308'425 optical modes. The output of the said multimode waveguide is then imaged with the optical system (230) onto a camera (240). In one embodiment, the camera is a sensitive CMOS camera with high speed output for connection to a computer system (250). The said camera has a high pixel count, such as standard Megapixel cameras. High speed means a frame rate of several hundred hertz to several tens of kilohertz. The image captured by the camera (240), synchronized to the input on the SLM (210), is transferred digitally to a digital computer (250). The input data (210) is converted to output data (240) in a non-linear manner given by optical propagation in the multimode waveguide (220). The output data (240) is said to be optically transformed or in other words optically computed. In the computer (250), a simple digital neural network with one (or few) layer (not shown) is digitally implemented by taking the output data (240) as the new input of the said digital one (or few) layer network. The digital output is computed as a weighted sum of the inputs. The weights (numbers) are the quantities learnt during the training phase. Hence, in this Opto-electronic computer, the first part of the computing is performed optically and the second part where learning occurs is performed digitally in a computer.

The nonlinear optical transformation is caused by the mode coupling induced by nonlinear effects. Mathematically, this transformation is expressed by a nonlinear Schrodinger equation: mode-coupling is caused by perturbations due to fiber bending or by impurities which acts as a linear mixer (via the coefficient $C_{p,n}$ in the second term in equation below). If the peak power of the pulse becomes important, non-linear coupling occurs in a significant manner as expressed by the non-linear coupling coefficient $\eta_{p,l,m,n}$. The terms A_n are the amplitude of the electric field mode n.

$$\frac{\partial A_p}{\partial z} = \underbrace{i\delta{\beta_0}^p A_p - \delta{\beta_1}^p \frac{\partial A_p}{\partial t} - i\frac{\beta_2}{2}\frac{\partial^2 A_p}{\partial t^2}}_{Propagation\ and\ Dispersion} + \underbrace{\sum_n C_{p,n} A_n}_{Linear\ Mode\ Coupling} + \underbrace{i\gamma \sum_{l,m,n} \eta_{p,l,m,n} A_l A_m {A_n}^*}_{Nonlinear\ Mode\ Coupling} \quad (1)$$

The computation performed by equation 1 can be modeled as a feed forward network. FIG 3 illustrates the network. The input is loaded onto the SLM (300) which transfers the information (phase or amplitude or both) to the optical field. The information is then decomposed to the waveguide modes, physically by focusing the light on the waveguide by lens 310, represented as the first layer of the network. For each step Δz - a small length along the waveguide – the linear and nonlinear coupling in the equation above is represented as a multi-layer feedforward connected network. This is repeated for each step until the fiber end.. With waveguide lengths of the order of several meters, the number of steps is very large (> 1000) so that the number of effective connections and thus optical computations become extremely large. After this computation, which is performed at the

time it takes light to propagate from one end of the fiber to the other at the speed of light, the result is converted back to electronic format on the camera (340). Physically, the waveguide output is imaged by a lens system (330) onto the camera (340).

By scaling the optical peak power of a laser source and adapting the waveguide length, any pulsed laser source (CW, nanosecond, picosecond or femtosecond) can be used in conjunction with any multimode waveguide supported wavelength (regardless of the sign of dispersion). A preferred embodiment is an electromagnetic radiation in the range from approximately 400 nm to 2000 nm for which pulsed laser sources from the femtosecond to nanosecond are available. This said spectral range is also appropriate for waveguide material structures and material that can guide light with low loss. Such waveguides include optical fibers such as those used in optical fiber communication with step-index and/or graded index structure or also other types such as photonic bandgap, hollow-core gas filled. In another embodiment, the multimode waveguides can be written in a planar photonic circuit such as a planar light guide circuit, also called photonic integrated circuit. Optical fiber material includes any material which guides light with low loss such as but not limited to fused silica, germanium doped, ytterbium doped, erbium doped, thulium doped, holmium doped. For photonic integrated circuits, silicon, silicon nitride and doped silicon, Indium Phosphide (InP), lithium Niobate (LiNbO3), Gallium Arsenide (GaAs) multimode waveguides are disclosed.

The principal advantage of this invention is the combination of the 3D connectivity of optics with the long interaction length and lateral confinement afforded by the waveguide which makes it possible to realize optical nonlinearities at relatively low power. At the same time, the large number of spatial modes that can be compactly supported in a multimode waveguide maintains the traditional high parallelism feature of optics, while maintaining a compact form factor. Finally, with the availability of megapixel spatial light modulators (SLMs) and cameras, the 2D input and output interfaces to the multimode waveguides can sustain a large information processing throughput.

FIG. 4 shows an experimental example of the disclosed optical computing invention. This example demonstrates learning a nonlinear function (sinc function: $\sin \pi x/\pi x$) from only input and output. This dataset is often used as a benchmark in machine learning studies since linear regression of a nonlinear function is impossible without transforming the information in a nonlinear manner. Each input value (x) was uniquely coded as a 2D pattern which was loaded on a phase SLM (FIG 2). By recording the nonlinearly propagated beam

profile of many such input values and then forming a digital neural network in the computer with one layer fed with the output data of the optical computation, a linear regression method was then performed digitally in the computer. To measure the effect of the spatiotemporal nonlinear propagation and assess the importance of the nonlinearity, different pulse peak powers were used to control the level of nonlinear propagation. With low peak power (1.14 kW), the function cannot be learned (400). By steadily increasing the laser peak power, nonlinear coupling is increased and the sinc function is better approximated with 2.29 kW (410). The best learning performance was achieved around 3.43 kW laser peak power (420). For this optimum power level, correct outputs were estimated from unseen test inputs with a root-mean-squared error (RMSE) of 0.0671. Further power increase (4.57kW) gradually deteriorated the performance of the nonlinear function learning (430) because, at this peak power, nonlinear pulse propagation give rise to a Raman beam clean-up regime and the beam profiles become virtually unaffected by the input data.

FIG 5 and FIG 6a-6b shows yet other experimental examples of the disclosed optical computing invention presented in FIG 1, however with complex data structures in these examples. FIG 5A shows the measured multivariable inference task with an Abalone dataset. FIG 5B shows the measured age prediction with a face image dataset. FIG 5C and 5D show the measured categorization tasks with an audio digit dataset. FIG 6a-6b show measured results for detecting COVID-19 diagnosis from X-ray images. The confusion matrix for the test dataset (a), categorization accuracy (b) and error evolution during the optimizing decision layer (c) are illustrating 93% success rate in diagnostics, which is on par with the state of the art best neural network trained for weeks on a vast network of computers. In this experiment, the respective features and images of the datasets were encoded as phase patterns onto the phase SLM with proper pixel scaling. The spatial distribution at the distal end of the multimode GRIN fiber facet was recorded, flattened (converted to a long 1D vector) and fed to the decision layer to perform linear regression. In all experiments above, the fiber length was 5 meters. The capabilities of the present invention is not limited by the illustrated examples. Further challlanging pattern recognition, learning and information processing tasks such as financial or biological data processing and predictions data can be easily adapted to the present invention.

The present invention can be realized with other embodiments. FIG 7 shows an example setup whereby a digital feedback is employed onto the optical beam to perform a memory effect akin to the pure digital feedback found for example in recurrent neural networks . The recorded spatial distribution of light on the camera (740) is processed via digital elements

such as but not limited to a FPGA or microprocessor. The digitally processed information can be used as a memory of the previous input signal by affecting the encoding of a new input signal on the SLM (710). FIG 8 illustrates another embodiment whereby the optical computing system of FIG. 2 is using an optical feedback to realize memory. Instead of a digital feedback loop between the processed data and the new input signal as in the embodiment in FIG 7, a free-space or waveguide-based optical feedback is provided by selecting a portion of the light in between the exit facet of the multimode waveguide (820) and the camera (840), to reinject it at the entrance facet of the multimode waveguide (820). FIG 9 illustrates yet another embodiment in which nonlinear information processing is controlled by external mechanical perturbations on the waveguide (920). As illustrated in FIG 2 and FIG 3, optical information processing is performed via nonlinear and linear coupling among the waveguide modes. The linear coupling can be modified by external perturbations to the waveguide. Combined with the nonlinear coupling, the introduced changes in linear coupling at small propagation steps can cause significant differences at the fiber end thus control over optical information processing can be achieved. The mechanical perturbation can be achieved by providing a mechanical force on the fiber to bend a radius of curvature. An array of piezoelectric actuators can be used to provide mechanical force. In this manner, the optical computing system is reconfigurable.

In another embodiment to perform control over the non-linear optical computing, FIG 10 shows an example setup to control the linear and non-linear coupling of the modes by utilizing an active component either as part of the multimode waveguide (1020) or in a cascade (spliced if it is a fiber or placed in close proximity or contact for other type of waveguides). The active component can be a gain medium powered by an external source such as, but not limited to a pump laser. The propagating optical information experiences amplification by the gain portion. This amplification affects the distribution of mode amplitudes via gain competition. To control this effect, pump light (1042) can be controlled with a second beam shaping element (1041) to impart a spatial control such as with a second SLM. Similar to the encoding of signal information, proper shaping of the pump light changes the effect of amplification and results in optical control over information processing. The pump light can be counter propagated to the optical information as indicated in FIG 10 or in the same direction as the optical information (not shown in FIG 10). In yet another embodiment, a spectrally and or spatially modulated pump light is brought from the side of the multimode waveguide as opposed to the beginning or end facet.

The present invention can be easily adapted to different waveguides for scaling or parallelization purposes. FIG 11 illustrate another embodiment in which the optical

information processing is realized by utilizing a multicore waveguide (1120) to scale and parallelize the computing power. As illustrated for FIG 2, the number of the modes of the waveguide can be increased to scale the optical information capacity of the computing system. A multicore waveguide can be utilized to increase this capacity even further. When the cores of these waveguides affect each other, due to promixity, the optical computation will be scaled. If the cores of the waveguide do not affect each other, one waveguide can be used to parallelize optical computing since each waveguide core acts as an individual waveguide.

Yet another embodiment is proposed and illustrated in FIG 12. A choice of material for the waveguides (1220) such as but not limited to silicon, lithium niobite, photonic crystal waveguides, hollow core waveguides, optofluidic waveguides can be used to realize the spatiotemporal nonlinear effect on the transported light by integrating the multimode waveguides in a planar integrated circuit. The photonic integrated circuits can be fabricated with a choice of material such as, but not limited to, silicon, silicon nitride and doped silicon, Indium Phosphide (InP), lithium Niobate (LiNbO3), Gallium Arsenide (GaAs) for the multimode waveguides. The acquisition section of the aforementioned methods can be integrated into the chip as illustrated in FIG 13. The imaging of the end of the multimode waveguide (1330) can modified as a tapered region to distribute the spatial information. The camera in the imaging system (1340) can be also integrated via detectors on the chip.

FIG 14 illustrates another embodiment as a variation of the embodiment of FIG. 2 in which the SLM (1410) which encodes the digital information from the computer (1460) onto optical pulses is divided into one or more areas. One or more area is used to encode the information to process and the remaining areas of the beam shaper can be utilized as pixels to reconfigure the linear and non-linear coupling inside the multimode waveguide (1420). Indeed, inside the waveguide (1420), spatiotemporal nonlinear propagation can be changed by controlling cross-phase modulation between the modes. The controlling pixels of the SLM (1410) are used to affect the cross-phase modulation and thus can alter the nonlinear information processing.

As mentioned earlier, the present invention furthermore presents a novel configurable optical computing system that can process information with high speed and energy efficiency. By utilizing different data injection, detection and optical system modification techniques, the system performs different data processing techniques with high accuracy.

Utilizing the optical information processing principle disclosed herein and in [Teğin, U., Moser, C., & Psaltis, D. (2020). Optical Computing with Spatiotemporal Nonlinearities. CH

01656/20.], this disclosure furthermore provides methods to reconfigure the optical computing system in order to customize the system for solving complex learning tasks with better accuracy and faster computing time. As mentioned above, our study showed that waveguides, such as multimode fibers (MMFs), can be utilized to achieve computation performance comparable to supercomputers for certaining tasks without the programmability presented herein below. By developing strategies to configure the optical computation scheme for optimal performance, the nonlinear optical transformation can perform even better for a much broader selection of computational tasks compared to its digital competitors.

Waveguide structures such as optical fibers can confine electromagnetic waves to small areas for long distances by total reflection on their boundaries. Thanks to this property, optical nonlinearities requiring very high electromagnetic powers per unit area can be efficiently realized within waveguides. If these waveguides can support different spatimodes, then nonlinear interactions manifest themselves both spatially and temporally. Herein it is demonstrated that spatiotemporal nonlinear effects can be utilized to process data optically, see also (Teğin, U., Yıldırım, M., Oğuz, İ., Moser, C., & Psaltis, D. (2020). Scalable Optical Learning Operator. arXiv preprint arXiv:2012.12404., Teğin, U., Moser, C., & Psaltis, D. (2020). Optical Computing with Spatiotemporal Nonlinearities. CH 01656/20.). However, without reconfiguration the optimal operation of the system for every task cannot be guaranteed. Hence, the present invention furthermore provides methods and apparatus to reconfigure the nonlinear spatiotemporal transform applied by the physical computational system in order to realize a universal optical computing system capable of performing diverse computation tasks with overall lower energy, faster learning and similar or better accuracy when compared to its digital counterparts. These aspects shall now be further illustrated with reference to FIG 15 to FIG 22.

In MMFs electromagnetic wave propagation can be decomposed to a set of discrete transverse mode channels. Information, expressed here as data are loaded as images or data matrices on a Spatial Light Modulator (SLM). The data on the SLM is encoded by light (i.e. a beam of light is illuminating the SLM) and then coupled to the MMF. The information is transferred to the mode domain of the optical fiber and the ensuing nonlinear transformation is not customized to the problem at hand. This suggests a need for shaping the information before the optical fiber to utilize it optimally for any dataset. FIG 15 illustrates a first embodiment. The digital preprocessing of data consists of a few convolutional layers. However, the training of these layers is not possible in the same manner with a fully digital

neural network since it is not possible to backpropagate error gradients through the fiber. Therefore, training of these layers is accomplished with, but not limited to, a reinforcement learning approach. The reinforcement learning algorithm modifies the weights of the preprocessing network (convolution kernel) to achieve higher success on the nonlinear transform's objective such as classification accuracy or regression precision. To determine the optimal modification to the preprocessing network either a set of physical experiments is done with different parameter configurations or parameters are searched digitally by creating a neural network model of the nonlinear system. Since this preprocessing network aims to transfer the most significant features of the data to the modes of the physical system, which do not change while the system is used, the layers of this digital preprocessing network can be transferred to other processing tasks with different types of datasets. Thus, FIG 15 depicts an example setup of the optical computing system that uses light modulated in space and time to control the light modulated with the data via an iterative digital control scheme.

In another embodiment, a portion of the SLM 1520 is reserved as the "control area", which is illuminated by a so-called control light beam. The SLM pixel values of the control area does not come from the dataset but from an algorithm aiming to maximize the performance of the computation on the given dataset (see FIG 15). The said control beam modified by the pixels of the control area is nonlinearly mixed with the data when coupled to the modes of the fiber 1530. The control pixels are then optimized to obtain a favorable nonlinear spatiotemporal interaction inside the waveguide 1530. The optimization can be realized with, but not limited to, a reinforcement learning (RL) approach. The RL algorithm optimizes the pixels of the SLM control area for different datasets, and optimal distributions for a particular computational task are then stored in a computer and utilized i.e. loaded into the control SLM for the perform the appropriate task optimally.

The temporal and spectral shape of intense light pulses determine the nonlinear interactions as they propagate through a medium [https://doi.org/10.1016/j.optlastec.2020.106439]. In a multimodal waveguide, the temporal properties of a pulse, such as its duration and amplitude and phase distribution also contributes to the nonlinear interaction because these interactions are coupled spatiotemporally. Therefore, the transformation of the spatially encoded control information is also highly dependent on the temporal characteristics of the light pulse. To exploit this dependence, the pulse shape used in our system is further controlled with a pulse shaper 1510 before it is spatially modulated. The pulse shaper 1510 includes an SLM (not shown in FIG 15) that alters the said parameters such as pulse length,

amplitude and phase. The said parameters are controlled with a reinforcement learning algorithm to obtain the optimal information transform inside the waveguide 1530 that performs a given machine learning task.

In addition to the modification of the data representation, the waveguide 1620 itself can be altered to modify linear and nonlinear interactions inside the waveguide 1620. In one embodiment, a temperature change is applied at different position along the length of the waveguide 1620 to perturb the wave propagation by changing the mode coupling strength between modes. This effect is for example used for sensing purposes [https://doi.org/10.1063/1.2344835]. In this invention, the change in temperature is used as a control mechanism to modify the waveguide properties to achieve an optimal data transform inside the waveguide 1620 (see FIG 16). The temperature of the waveguide 1620 is locally controlled at many different positions by means of an array of Peltier plates or resistor wires. Thus, FIG 16 depicts an example setup of the optical computing system with temperature based control scheme.

In another embodiment illustrated in FIG 17, parallel access to the same SLM 1710 and cameras 1730 such as CCDs or CMOS, which are expensive, is achieved with several waveguides 1720. The high space bandwidth product of SLM 1710 and cameras 1730 is then divided by the smaller space bandwidth product of the waveguides 1720.
Similarly, the high spectral- time bandwidth product of a single mode waveguide 1720 can be used to combine multiple wavelength data and control channels in a single waveguide 1720. Both said methods above can also be combined. Thus, FIG 17 depicts an example setup of the optical computing system with parallelized waveguides that share the illumination source 1700 and data.

In yet another embodiment of the optical computation framework is reconfigured by different light wavelength. To achieve this goal multiple wavelengths of light, either without spatial modulation or with spatial modulation via an SLM 1810, are coupled to the same waveguide 1820 simultaneously. These different wavelengths affect nonlinearly each other with a phenomenon such as four wave mixing or they can be used to independently do transformations on different data with effects such as self-phase modulation (see FIG 18). In addition, the computation can be parallelized in terms of simultaneously applying different transforms on the same data by coupling the same information to multiple similar or dissimilar waveguides. Many different transforms on the same data with different waveguides could unveil information on features of different scales. Moreover, compared

to multimode waveguides, currently SLM and cameras are much more costly, hence encoding and reading information from many waveguides with single SLM and camera is expected to be a cost-effective performance improvement to the system. Thus, FIG 18 depicts an example setup of the optical computing system reconfigurable with different wavelength of light spatially modulated.

FIG 19 illustrates another embodiment to obtain spectral information, in addition to purely spatial information, at the output of the waveguide 1920. In an imaging setup, one acquires purely spatial information. An optical element 1930 such as grating or prism spectrally disperses the spatial information along the axis of diffraction, dispersion which provides an additional frequency content to the spatial content. Thus, a spatial measurement via a camera 1940 after the dispersive element 1930 contains the temporal frequency content of the light as well as the spatial information. Due to optical spatiotemporal nonlinear interactions, the frequency distribution of the information-carrying pulse undergoes nonlinear changes similar to spatial changes. With such an apparatus the spatiotemporal nonlinear interactions utilized for information mapping manifest themselves in a measurement containing temporal and spatial changes simultaneously.

In FIG 19, the spectral information is overlapped with the spatial information. In a subsequent embodiment (image not shown), the spatial and spectral information can be separated in the following manner. The input side of the multimode waveguide is composed of a multitude of near single mode waveguides, so called multicore waveguides. The arrangement of individual cores of the input waveguide is oriented in a circular or square shape to match the arrangement of the pixels on the SLM. The distal side of the waveguide is arranged as a juxtaposition of individual near single mode waveguides, one adjacent to the next thus forming a line of waveguides. The light emitted from the distal side of the waveguide thus forms a 1D line which is diffracted to form a 2D image captured by a camera. The image has spectral content in one axis and spatial content in the orthogonal axis. Thus, FIG 19 depicts an example setup of the optical computing system with a dispersive optical element to resolve temporal effects with spatial information.

FIG 20 discloses another embodiment to increase the extracted information from the aforementioned optical computing system. The linearly or circularly polarized light entering a non-polarization maintaining waveguide 2020, such as but not limited to a optical multimode fiber, undergoes polarization changes due to propagation in the waveguide 2020. Using a polarization beam splitter 2030 or the like, a measurement resolving two axes

of polarization (s-polarization and p-polarization) can increase the information acquired from the waveguide-based optical computing system. For different polarization distribution, the spatial distribution of the light alters and as illustrated in FIG 20, extracted information from the optical system can be doubled. Simultaneous measurement with concatenating, adding, or subtracting, one can increase the accuracy of optical computation in the physical computing framework. Thus, FIG 20 depicts an example setup of the optical computing system with a polarization sensitive optical element.

FIG 21 discloses another embodiment to control the aforementioned optical computing system. Similar to FIG 16, control over the multimode waveguide 2120 is implemented with electro-optically modulating propagating inside the waveguide 2120. This can be achieved with an externally applied altering electric-field which is distributed over the waveguide 2120 of the interest. Thus the propagating optical field inside the waveguide 2120 can be modulated and the control over the setup can be achieved. Thus, FIG 21 depicts an example setup of the optical computing system reconfigurable with electro-optically controllable waveguide.

In another embodiment to obtain additional control in the optical computing system, the previously described system can be set up in a cascaded manner. Light can couple to multiple waveguides 2220 positioned one after another and in between these waveguides 2220 additional spatial light modulators can be placed, whose pixels are control pixels. This way the data transform can be controlled with consecutive SLMs 2210 or information with feature count higher than one SLM's pixel count can be processed. (FIG 22).

CLAIMS

1. A device for optical computing, in particular for implementing machine learning such as an artificial neural network, the device comprising:
   - at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210); and
   - at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220);

   wherein the at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) is configured to modulate incident radiation, whereby input radiation is generated, and

   wherein the at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320) is configured to guide the input radiation along a propagation direction,

   characterized in that the at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to nonlinearly optically transform the input radiation propagating in the at least one waveguide, whereby output radiation that is outputted from the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is optically computed.

2. The device according to claim 1, wherein the device is configured such, that the output radiation being outputted from the waveguide is optically transformed, whereby a transformed optical signal is generated,

   wherein the device further comprises at least one detection device such as a camera that is configured to detect the transformed optical signal and to digitize the detected transformed optical signal, whereby digital output data is generated, and

   wherein the device further comprises an electronic device such as a computer that is configured to receive the digital output data, and

   wherein the electronic device comprises a digital neural network that is configured to be trained with the digital output data.

3. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to generate a mode coupling of the input radiation propagating in the waveguide, and wherein said mode coupling is preferably induced

by nonlinear effects of the waveguide.

4. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to generate a linear mode coupling and/or a nonlinear mode coupling of the input radiation propagating in the waveguide.

5. The device according to the previous claims, wherein the device is configured to optically process information via the linear mode coupling and/or the nonlinear mode coupling.

6. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to decompose the input radiation propagating along the propagation direction into one or more modes.

7. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to nonlinearly optically transform the input radiation being propagating in the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) upon a perturbation of the waveguide, and

wherein the perturbation of the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) preferably corresponds to a bending of the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) and/or to one or more impurities of the waveguide.

8. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to nonlinearly optically transform the input radiation being propagating in the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) based on the following equation:

$$\frac{\partial A_p}{\partial z} = \underbrace{i\delta\beta_0{}^p A_p - \delta\beta_1{}^p \frac{\partial A_p}{\partial t} - i\frac{\beta_2}{2}\frac{\partial^2 A_p}{\partial t^2}} + \underbrace{\sum_n C_{p,n} A_n} + \underbrace{i\gamma \sum_{l,m,n} \eta_{p,l,m,n} A_l A_m A_n{}^*},$$

wherein the term A_n corresponds to the amplitude of the electric field mode n,

wherein $\eta_{p,l,m,n}$ are nonlinear coupling coefficients,

wherein $C_{p,n}$ is a linear coefficient, and

wherein β_0, β_1 and β_2 are dispersion terms.

9. The device according to claim 8, wherein the device is configured such that the computation performed by the said equation is implementable as a feed forward network.

10. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is a multicore waveguide, and wherein said multicore waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is arranged and configured such as to scale and parallelize a computing power of the device.

11. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is written in a photonic circuit, preferably in a planar photonic circuit such as a planar light guide circuit or photonic integrated circuit, and

wherein the photonic circuit preferably comprises or consists of at least one of: silicon, silicon nitride and doped silicon, Indium Phosphide (InP), lithium Niobate (LiNbO3), Gallium Arsenide (GaAs) for the multimode waveguides.

12. The device according to any one of the preceding claims, wherein the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) is a spatial light modulator, preferably a megapixel spatial light modulator, and/or

wherein the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) is a temporal modulator that is configured to temporally modulate incident radiation.

13. The device according to any one of the preceding claims, wherein the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) is configured to modulate a phase of incident radiation and/or an

amplitude of incident radiation.

14. The device according to any one of the preceding claims, wherein the device is configured to encode information such as a phase information and/or an amplitude information on radiation.

15. The device according to any one of the preceding claims, wherein the input radiation generated by the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) comprises encoded information such as a phase information and/or an amplitude information, a phase information preferably corresponding to a phase pattern and an amplitude information preferably corresponding to an amplitude pattern.

16. The device according to any one of the preceding claims, further comprising at least one detection device (240, 740, 840, 940, 1040, 1140, 1240, 1340, 1440, 1540, 1630, 1730, 1830, 1940, 2040, 2130, 2230) being configured to detect the output radiation and to generate at least one detection signal based on the detected output radiation.

17. The device according to any one of the previous claims, further comprising at least one feedback device that is configured to provide at least one feedback signal being associated with the output radiation to the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) and/or to the input radiation and/or to a radiation source (200, 700, 800, 900, 1000, 1100, 1200, 1300) being configured to emit radiation.

18. The device according to claim 17, wherein the feedback device is in communication with the detection device (240, 740, 840, 940, 1040, 1140, 1240 1340, 1440, 1540, 1630, 1730, 1830, 1940, 2040, 2130, 2230) and/or with the output radiation.

19. The device according to any one of claims 17 to 18, wherein the feedback device is configured to affect the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) based on the detection signal.

20. The device according to any one of claims 17 to 19, wherein the feedback device is

configured to use the detection signal as a memory of a previous input signal to the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) that resulted in the output radiation being associated with the said detection signal by affecting an encoding of a new input signal on the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210).

21. The device according to any one of claims 17 to 20, wherein the feedback device is a digital feedback device, preferably a microprocessor or an integrated circuit such as a field-programmable gate array.

22. The device according to claim 17, wherein the feedback device is configured to inject a portion of the output radiation being emitted from an exit facet of the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) into an entrance facet of the waveguide.

23. The device according to claim 17 or 22, wherein the feedback device is an optical feedback device, the optical feedback device preferably being configured to provide a free-space or a waveguide-based feedback.

24. The device according to any one of the preceding claims, further comprising at least one perturbation device that is configured to introduce perturbations on the waveguide.

25. The device according to claim 24, wherein the perturbations are mechanical perturbations, and/or

wherein the perturbations are caused by the application of a mechanical force on the waveguide, said mechanical force particularly preferably bends a radius of curvature of the waveguide.

26. The device according to any one of claims 24 to 25, wherein the perturbation device is configured to modify the linear coupling mode of the input radiation propagating in the waveguide, and/or

wherein the perturbation device is configured to control a nonlinear information processing performed by the device.

27. The device according to any one of the preceding claims, further comprising an amplification device, wherein the amplification device is configured to amplify input radiation propagating in the waveguide.

28. The device according to claim 27, wherein the amplification device is configured to affect a distribution of the mode amplitudes of the input radiation propagating in the waveguide, preferably via gain competition, and/or

wherein the amplification device is configured to modify the linear coupling mode and the nonlinear coupling mode of the input radiation propagating in the waveguide, and/or

wherein the amplification device is configured to control a nonlinear information processing performed by the device.

29. The device according to any one of claims 27 to 28, wherein the amplification device further comprises at least one control element that is configured to spatially and/or spectrally control an action of the amplification device, in particular of a gain medium, on the waveguide, said control element preferably being a beam shaping element.

30. The device according to any one of claims 27 to 29, wherein the amplification device comprises a laser, and wherein the amplification device is arranged such, that radiation being emitted from said laser is:
i) counter-propagating to the input radiation in the wave guide, or
ii) propagating along the same direction as the input radiation in the waveguide, or
iii) propagating along a direction being perpendicular to an extension direction of the wave guide.

31. The device according to any one of the preceding claims, wherein the device is further configured to change a spatiotemporal nonlinear propagation of the input radiation in the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320) by controlling a cross-phase modulation between the modes of the input radiation propagating in the waveguide.

32. The device according to any one of the preceding claims, wherein the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) is divided into two or more areas, and wherein one or more areas are configured to encode information to process by the device and the remaining

areas are configured to reconfigure a mode coupling, in particular a nonlinear mode coupling and/or a linear mode coupling of the input radiation propagating in the waveguide.

33. The device according to claim 32, wherein the remaining areas are configured to affect a cross-phase modulation between the modes of the waveguide, the remaining areas preferably corresponding to pixels of a spatial light modulator.

34. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to generate a spatiotemporal nonlinear pulse propagation of the input radiation propagating in the waveguide.

35. The device according to claim 34, wherein the device is configured to implement one or more machine learning technics using the spatiotemporal nonlinear pulse propagation in the waveguide.

36. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) constitutes and/or provides at least one optical layer of a neural network.

37. The device according to any one of the preceding claims, wherein the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) defines a length with respect to the propagation direction, and wherein a length section of said length represents a multi-layer feedforward connected network.

38. The device according to any one of the preceding claims, wherein the device is configured to perform an optical computation within a time duration corresponding to the time duration required for the input radiation to propagate along a length of the waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) at the speed of light.

39. The device according to claim 38, wherein the device is configured to perform a nonlinear optical mapping between the radiation being incident on the modulator

(210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) and the at least one detection signal.

40. The device according to claim 39, wherein the device is further configured to combine the nonlinear optical mapping with at least one layer of a neural network, preferably at least one single-layer and/or at least one digital layer of a neural network, particularly preferably with at least one digital single-layer of neural network.

41. The device according to claim 40, wherein the layer of the neural network is implemented in an electronic device (250, 750, 850, 950, 1050, 1150, 1250, 1350) such as a computer, and/or

wherein the layer of the neural network is trained to recognize the at least one detection signal.

42. The device according to any one of claims 40 to 41, wherein the layer of the neural network is trained with a set of input-output pairs, and wherein said input-output pairs correspond to pairs of a particular input radiation being generated by the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) and a particular detection signal being generated by the detection device (240, 740, 840, 940, 1040, 1140, 1240 1340, 1440, 1540, 1630, 1730, 1830, 1940, 2040, 2130, 2230) upon detection of the output radiation corresponding to said input radiation.

43. The device according to any one of claims 39 to 42, wherein the device is configured such, that the detection signal is taken as a new input signal of the layer of the neural network, and/or

wherein an output signal being generated by the neural network is computed as a weighted sum of the detection signal, the weights of the weighted sum preferably are quantities learnt by the neural network during a training phase.

44. The device according to any one of the preceding claims, wherein the device comprises or corresponds to an optical processor, the optical processor preferably being a reconfigurable optical processor.

45. The device according to any one of the preceding claims, wherein the device further

comprises at least one optically dispersive element (1930), wherein said optically dispersive element (1930) is configured to optically disperse the output radiation, whereby the output radiation is spatially and spectrally optically distributed, and/or

wherein the device further comprises at least one filtering element, wherein the filtering element is configured to filter one or more wavelengths.

46. The device according to any one of the preceding claims, wherein the waveguide (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) comprises a multitude of multicore waveguides,

wherein each multicore waveguide comprises a core defining an entrance facet and an exit facet,

wherein the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210) comprises a multitude of pixels, and

wherein an arrangement of the entrance facets of the cores matches an arrangement of the pixels of the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210), and/or

wherein the exit facets of the cores are arranged in juxtaposition.

47. The device according to any one of the preceding claims, further comprising at least one polarization selective optical element (2030), wherein said polarization selective element (2030) is configured to distribute the output radiation according to its states of polarization, and

wherein the polarization selective optical element (2030) preferably corresponds to a polarizing beam splitter.

48. The device according to any one of the preceding claims, further comprising at least one radiation source (200, 700, 800, 900, 1000, 1100, 1200, 1300, 1500, 1600, 1700, 1800, 1900, 2000) being configured to emit radiation, and

wherein the radiation source is arranged such, that its emitted radiation is incident on the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2120, 2210), whereby the input radiation is generated.

49. The device according to any one of the preceding claims, further comprising at least one reconfiguration arrangement,

wherein the reconfiguration arrangement is configured to reconfigure a nonlinear optical transformation and preferably additionally a linear optical transformation of the input radiation propagating in the waveguide (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220).

50. The device according to claim 49, wherein the reconfiguration arrangement is configured to reconfigure information to be processed by the device and/or the waveguide (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) and/or the input radiation being propagating in the waveguide and/or the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) and/or radiation being incident on the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210).

51. The device according to claim 49 or 50, wherein the reconfiguration arrangement comprises at least one pulse shaping device (1510) that is configured to shape a pulse of radiation, whereby pulsed-shaped radiation is generated, the pulse shaping device (1510) preferably being configured to alter a temporal shape and/or a spatial shape such as a pulse length and/or a pulse amplitude and/or a pulse phase of the pulse of radiation and

wherein said pulse-shaped radiation is incident on the modulator (1520).

52. The device according to any one of claims 49 to 51, wherein the reconfiguration arrangement comprises the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210),

wherein the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) is divided into two or more areas,

wherein one or more areas are configured to receive information to be processed by the device and to be irradiated with radiation, whereby the information is encoded by the irradiated radiation,

wherein one or more remaining areas of the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) are configured to be irradiated with radiation, whereby control radiation is generated, and

wherein the device is configured to preferably nonlinearly mix said control radiation with the encoded information when the control radiation and the encoded information are propagating in the waveguide (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220).

53. The device according to any one of claims 49 to 52, wherein the reconfiguration arrangement comprises at least one preprocessing device, wherein said preprocessing device is configured to receive and preprocess information to be processed by the device, whereby preprocessed information is generated, and

wherein the preprocessing device is further configured to transfer said preprocessed information to the modulator (1520).

54. The device according to any one of claims 49 to 53, wherein the reconfiguration arrangement comprises at least one perturbation device that is configured to introduce perturbations on the waveguide (1620, 2120), and

wherein the perturbation device is preferably configured to non-mechanically and/or mechanically perturb the waveguide (1620, 2120), and/or

wherein the perturbation device preferably corresponds to the perturbation device as claimed in any one of claims 24 to 26.

55. The device according to claim 54, wherein the perturbation device is configured to apply a temperature change to the waveguide (1620), and/or

wherein the perturbation device comprises one or more heating elements being configured to heat the waveguide (1620) and/or one or more cooling elements being configured to cool the waveguide, the perturbation device preferably being a Peltier plate or a resistor wire, and/or

wherein the perturbation device is configured to apply an electric field to the waveguide (2120).

56. The device according to any one of claims 49 to 55, wherein the reconfiguration arrangement comprises at least one waveguide, wherein said waveguide is configured to receive at least part of the input radiation from the modulator (1710) and to nonlinearly optically transform the input radiation propagating in the further waveguide, whereby further output radiation that is outputted from the waveguide of the reconfiguration arrangement is generated, and

wherein the waveguide (1720) and the waveguide of the reconfiguration

arrangement are preferably arranged parallel to one another, and/or

wherein the output radiation from the waveguide (1720) and the further output radiation from the waveguide of the reconfiguration arrangement are preferably detectable by a common detection device.

57. The device according to claim 56, wherein the waveguide (1720) and the waveguide of the reconfiguration arrangement are the same, and wherein the input radiation being propagating in the waveguide (1720) and the input radiation propagating in the waveguide of the reconfiguration arrangement differ from one another, or

wherein the waveguide (1720) and the waveguide of the reconfiguration arrangement differ from one another, and wherein the input radiation being propagating in the waveguide (1720) and the input radiation propagating in the waveguide of the reconfiguration arrangement are the same, the waveguide and the waveguide of the reconfiguration arrangement preferably differ in their core sizes and/or their numerical aperture.

58. The device according to any one of claims 49 to 57, wherein the waveguide forms part of the reconfiguration arrangement,

wherein the waveguide is a single-mode waveguide and the modulator is a temporal modulator.

59. The device according to any one of claims 49 to 58, wherein the reconfiguration arrangement comprises at least one radiation source (1800) being configured to emit radiation,

wherein the device is configured such that the input radiation and said radiation are propagating simultaneously in the waveguide (1820), and
wherein a wavelength of the input radiation differs from a wavelength of said radiation.

60. The device according to any one of claims 49 to 59, wherein the reconfiguration arrangement comprises at least one modulator and at least one waveguide,

wherein the modulator of the reconfiguration arrangement is arranged so as to receive the output radiation, whereby modulated input radiation is generated, and

wherein the waveguide of the reconfiguration arrangement is configured to nonlinearly optically transform the modulated input radiation propagating, whereby further output radiation is outputted from said waveguide.

61. The device according to any one of claims 49 to 60, wherein the reconfiguration arrangement furthermore comprises at least one optimization device, wherein the optimization device is configured to optimize the nonlinear optical transformation and preferably additionally the linear optical transformation of the input radiation propagating in the waveguide, and

wherein the optimization device is configured to provide at least one optimization signal being associated with the output radiation and/or the further output radiation to the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) and/or to the waveguide and/or to the perturbation device and/or to the pulse-shaping device and/or to the preprocessing device and/or to the modulator of the reconfiguration arrangement.

62. The device according to claim 61, wherein the optimization device is configured to produce the optimization signal by applying one or more digital operations such as regression and classification and/or by applying one more machine learning algorithms such as reinforcement learning and/or by applying one or more evolutionary algorithms such as a genetic algorithm.

63. The device according to claim 61 or 62, wherein the optimization device is configured to produce the optimization signal based on one or more detection signals being generated by one or more detection devices that are configured to detect the output radiation and/or the further output radiation, and

wherein said one or more detection signals are preferably used as a preprocessing input signal to one or more layers of a preprocessing network of the preprocessing device.

64. The device according to any one of claims 61 to 63, wherein the optimization device is in communication with the pulse shaping device, and wherein the optimization signal optimizes the shaping of the pulse of radiation such as pulse length and/or pulse amplitude and/or pulse phase.

65. The device according to any one of claims 61 to 64, wherein the optimization device is in communication with the one or more remaining areas of the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) being configured to be irradiated with radiation, wherein said one or

more areas comprise pixels, and wherein the optimization signal optimizes the pixels.

66. The device according to any one of claims 61 to 65, wherein the optimization device is in communication with the preprocessing device, wherein the preprocessing device comprises a preprocessing network with weights, and wherein the optimization signal optimizes the weights of the preprocessing network.

67. A system for optical computing, in particular for implementing machine learning such as implementing an artificial neural network, the system comprising:

- at least one radiation source (200, 700, 800, 900, 1000, 1100, 1200, 1300);
- at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220);
- at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220);
- at least one detection device (240, 740, 840, 940, 1040, 1140, 1240 1340, 1440, 1540, 1630, 1730, 1830, 1940, 2040, 2130, 2230); and
- at least one output device (250, 750, 850, 950, 1050, 1150, 1250, 1350),

wherein the at least one radiation source (200, 700, 800, 900, 1000, 1100, 1200, 1300) is configured to emit radiation,

wherein the at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) is configured to modulate incident radiation being emitted from the at least one radiation source (200, 700, 800, 900, 1000, 1100, 1200, 1300), whereby input radiation is generated,

wherein the at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to guide the input radiation along a propagation direction, whereby output radiation is generated,

wherein the at least one detection device (240, 740, 840, 940, 1040, 1140, 1240 1340, 1440, 1540, 1630, 1730, 1830, 1940, 2040, 2130, 2230) is configured to detect the output radiation, to generate at least one detection signal based on the detected output radiation, and to transmit the at least detection signal to the at least one output device (250, 750, 850, 950, 1050, 1150, 1250, 1350),

wherein the at least one output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) is configured to generate at least one output signal based on the at least one detection signal and to transmit the at least one output signal to the at least

one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210), characterized in that the at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to optically transform the input radiation propagating in the at least one waveguide in a nonlinear manner, whereby the output radiation is optically computed

68. The system according to claim 67, wherein the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) is an electronic device such as a computer.

69. The system according to any one of claims 67 to 68, wherein the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) comprises at least one layer of a neural network.

70. The system according to any one of claims 67 to 69, wherein the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) is configured to generate one or more layers of a neural network, and

wherein the one or more layers preferably are digital one or more layers of a neural network, and/or

wherein the one or more layers are preferably generated with random weights.

71. The system according to claim 70, wherein the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) is configured to propagate the at least one detection signal through the one or more layers of the neural network, whereby at least one actual output signal is generated.

72. The system according to claim 71, wherein the actual output signal corresponds to the output signal being transmitted from the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) to the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210).

73. The system according to claim 71 or 72, wherein the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) is further configured to generate at least one error signal based on the at least one actual output signal and at least one target output signal,

wherein the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) is further configured to propagate the at least one error signal back to the neural network so as to update one or more weights being associated with the one or more layers of the neural network.

74. The system according to any one of claims 70 to 73, wherein the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) is further configured to propagate at least one further detection signal through the one or more layers of the neural network being associated with the updated one or more weights, whereby at least one further actual output signal is generated, and

wherein the at least one further actual output signal corresponds to the output signal being transmitted from the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) to the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210).

75. The system according to claim 73 or 74, wherein the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) is configured to generate the target output signal based on at least one set of input-output pairs, and wherein said input-output pairs correspond to pairs of a particular input radiation being generated by the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) and a particular detection signal being generated by the detection device (240, 740, 840, 940, 1040, 1140, 1240 1340, 1440, 1540, 1630, 1730, 1830, 1940, 2040, 2130, 2230) upon detection of the output radiation corresponding to said input radiation.

76. The system according to any one of claims 67 to 75, wherein the at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is a multimode waveguide that is configured to decompose the input radiation into one or more modes, whereby the output radiation is generated as a result of non-linear coupling and preferably additionally of linear coupling between the modes.

77. The system according to any one of claims 67 to 76, wherein the system constitutes an opto-electronic computer.

78. The system according to any one of claims 67 to 77, further comprising at least one

reconfiguration arrangement as claimed in any one of claims 49 to 66.

79. A method for optical computing, in particular for machine learning computations such as artificial neural network computations, the method comprising the steps of:

- Modulating incident radiation being emitted from at least one radiation source (200, 700, 800, 900, 1000, 1100, 1200, 1300) with at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210), whereby input radiation is generated;
- Guiding the input radiation in at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) along a propagation direction, whereby output radiation is generated;
- Detecting the output radiation and generating at least one detection signal based on the detected output radiation with at least one detection device (240, 740, 840, 940, 1040, 1140, 1240 1340, 1440, 1540, 1630, 1730, 1830, 1940, 2040, 2130, 2230);
- Transmitting the at least one detection signal to at least one output device (250, 750, 850, 950, 1050, 1150, 1250, 1350);
- Generating at least one output signal based on the at least one detection signal with the at least one output device (250, 750, 850, 950, 1050, 1150, 1250, 1350);
- Transmitting the at least one output signal from the at least one output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) to the at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210); and
- Modulating further radiation being emitted from the at least one radiation source (200, 700, 800, 900, 1000, 1100, 1200, 1300) with the at least one modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) based on the at least one output signal,

characterized in that the at least one waveguide (220, 720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) is configured to optically transform the input radiation propagating in the at least one waveguide in a nonlinear manner, whereby the output radiation is optically computed.

80. The method according to claim 79, further comprising the step of performing an optical computation within a time duration corresponding to the time duration required for the input radiation to propagate along a length of the waveguide (220,

720, 820, 920, 1020, 1120, 1220, 1320, 1420, 1530, 1620, 1720, 1820, 1920, 2020, 2120, 2220) at the speed of light.

81. The method according to claim 79 or 80, further comprising the step of performing a nonlinear optical mapping between the radiation being incident on the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) and the at least one detection signal.

82. The method according to claim 81, further comprising the step of combining the nonlinear optical mapping with at least one layer of a neural network, preferably at least one single-layer and/or at least one digital layer of a neural network, particularly preferably with at least one digital single-layer of neural network being implemented in the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350).

83. The method according to any one of claims 79 to 82, further comprising the step of training at least one layer of a neural network being implemented in the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) to recognize the at least one detection signal.

84. The method according to any one of claims 79 to 83, further comprising the step of training at least one layer of a neural network being implemented in the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) with a set of input-output pairs, and wherein said input-output pairs correspond to pairs of a particular input radiation being generated by the modulator (210, 710, 810, 910, 1010, 1110, 1210, 1310, 1410, 1520, 1610, 1710, 1810, 1910, 2010, 2110, 2210) and a particular detection signal being generated by the detection device (240, 740, 840, 940, 1040, 1140, 1240 1340, 1440, 1540, 1630, 1730, 1830, 1940, 2040, 2130, 2230) upon detection of the output radiation corresponding to said input radiation.

85. The method according to any one of claims 79 to 84, further comprising the step of taking the detection signal as a new input signal of at least one layer of a neural network being implemented in the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350).

86. The method according to any one of claims 79 to 85, further comprising the step of computing an output signal being generated by at least one layer of a neural network

being implemented in the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) as a weighted sum of the detection signal, the weights of the weighted sum preferably are quantities learnt by the neural network during a training phase.

87. The method according to any one of claims 79 to 86, further comprising the step of forming a digital neural network in the output device (250, 750, 850, 950, 1050, 1150, 1250, 1350) with at least one layer fed with the detection signal.

88. The method according to any one of claims 79 to 87, further comprising the step of nonlinear optical transformation and preferably additionally a linear optical transformation of the input radiation propagating in the waveguide using a reconfiguration arrangement as claimed in any one of claims 49 to 66.

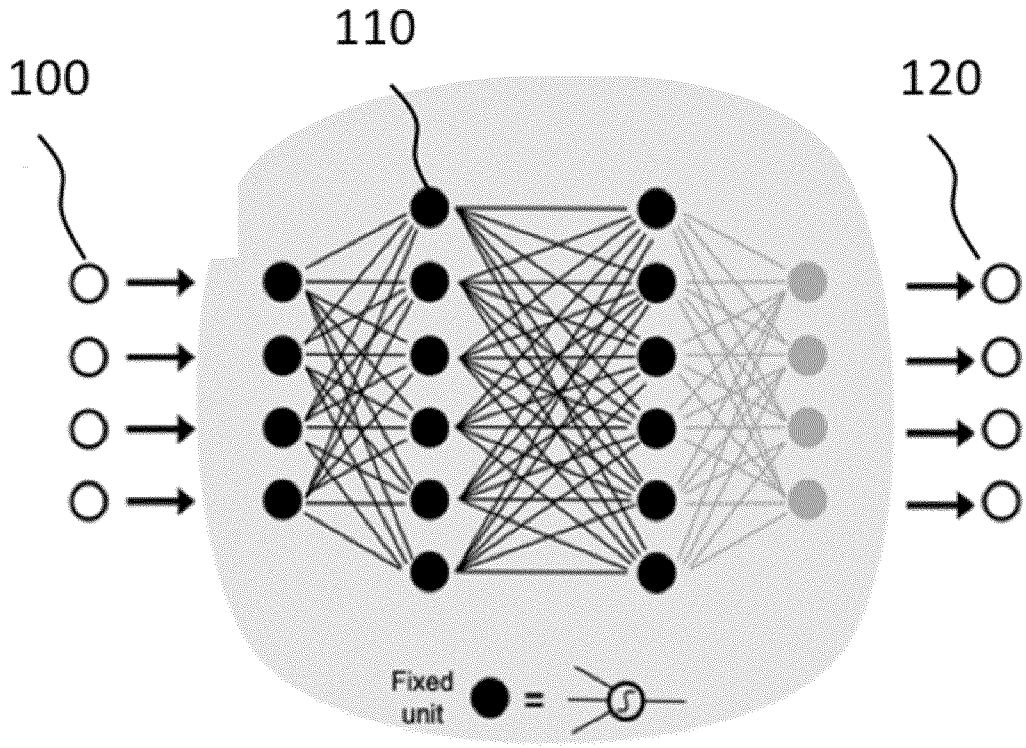


FIG. 1a

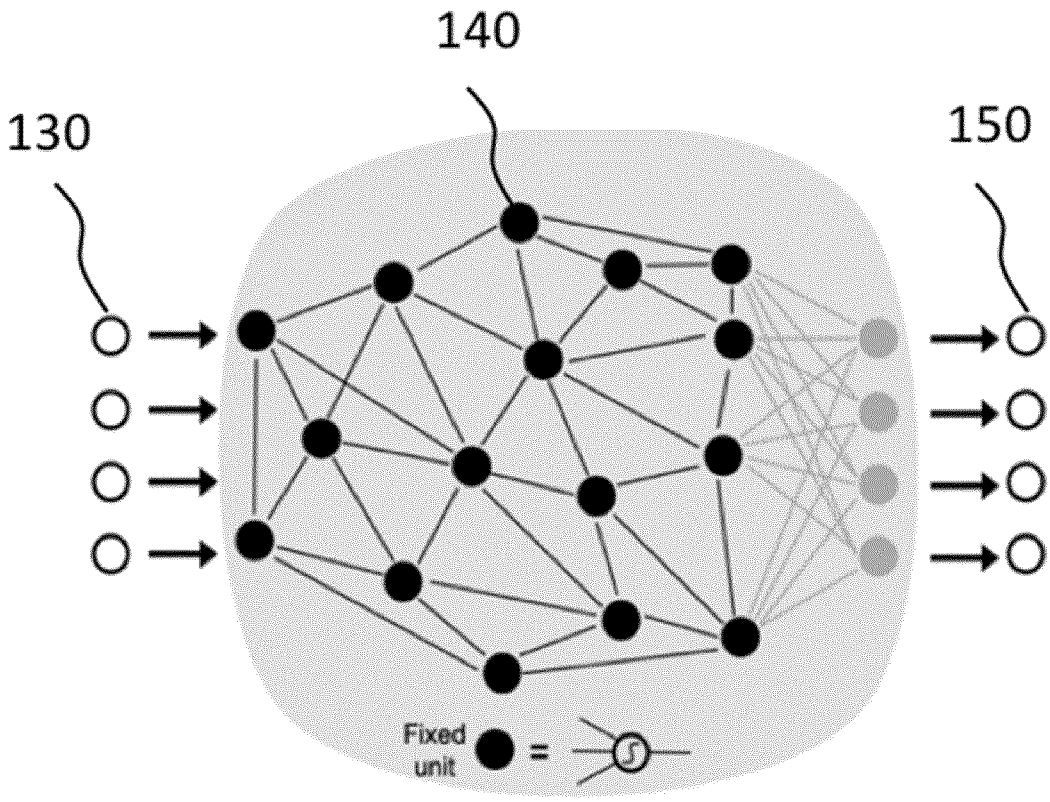


FIG. 1b

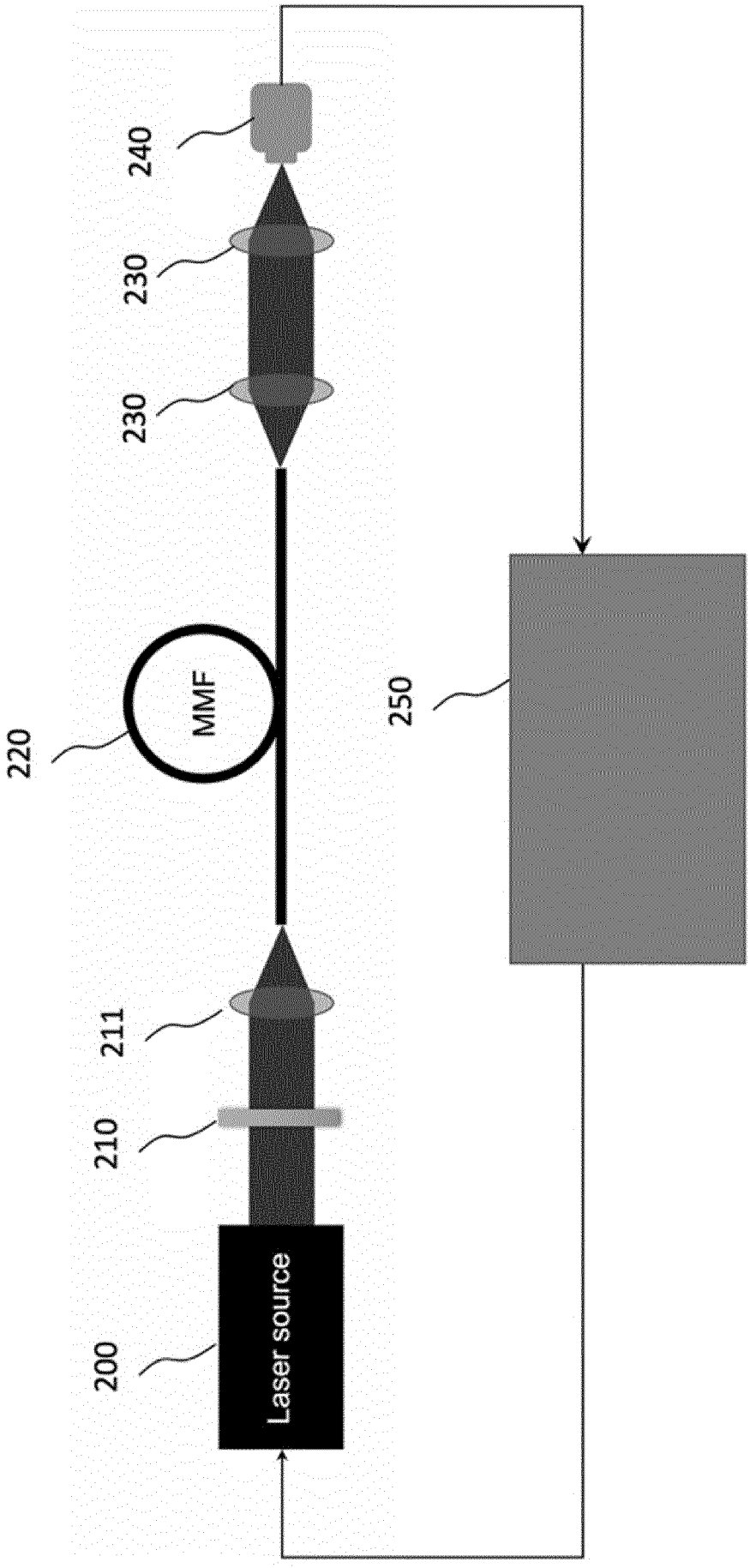


FIG. 2

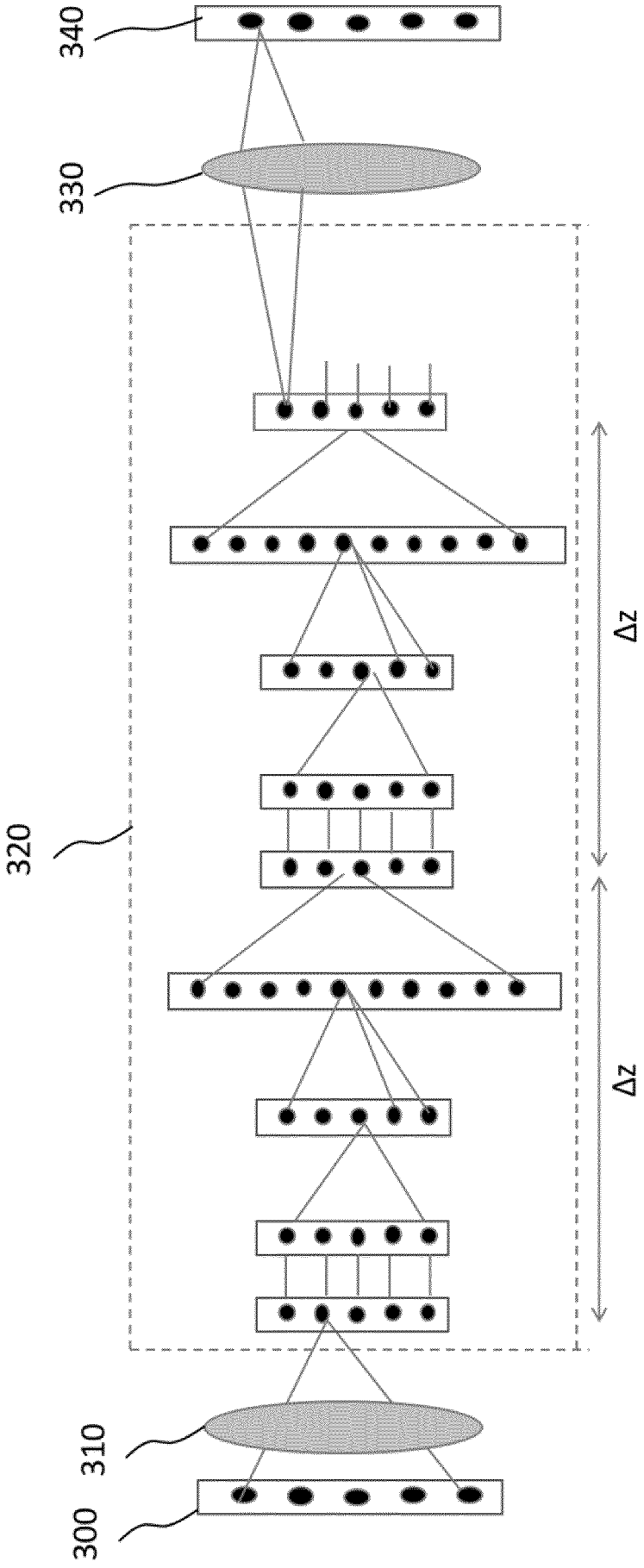


FIG. 3

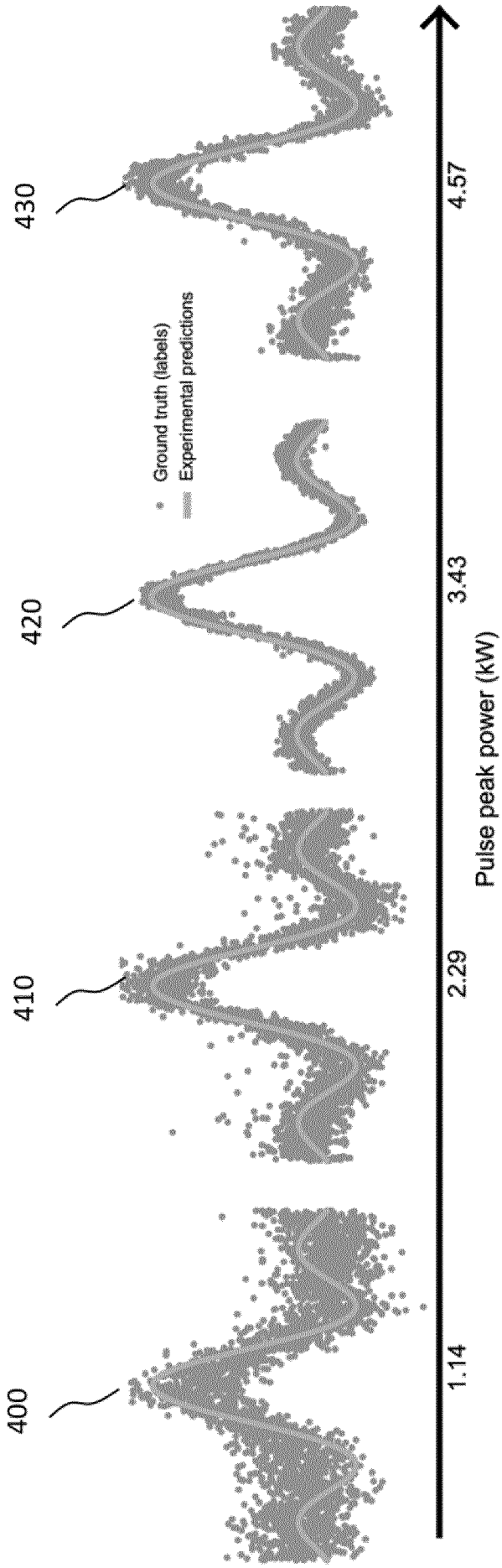

400
410
420
430
Ground truth (labels)
Experimental predictions
1.14
2.29
3.43
4.57
Pulse peak power (kW)

FIG. 4



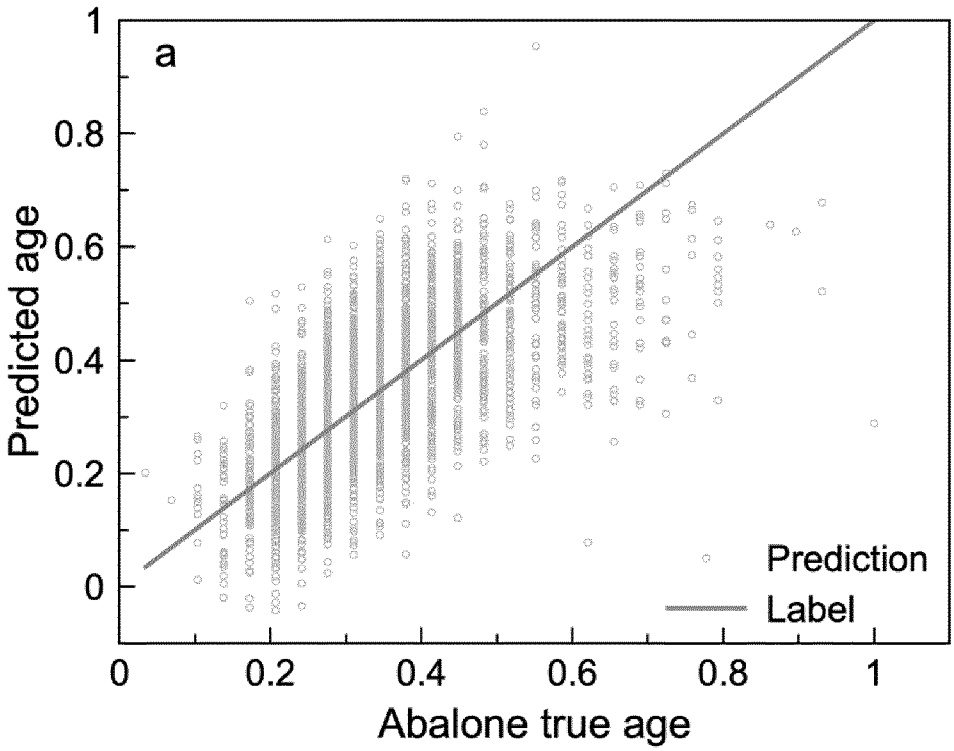

a
Predicted age
Abalone true age
Prediction
Label
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0.4
0.6
0.8
1

FIG. 5a

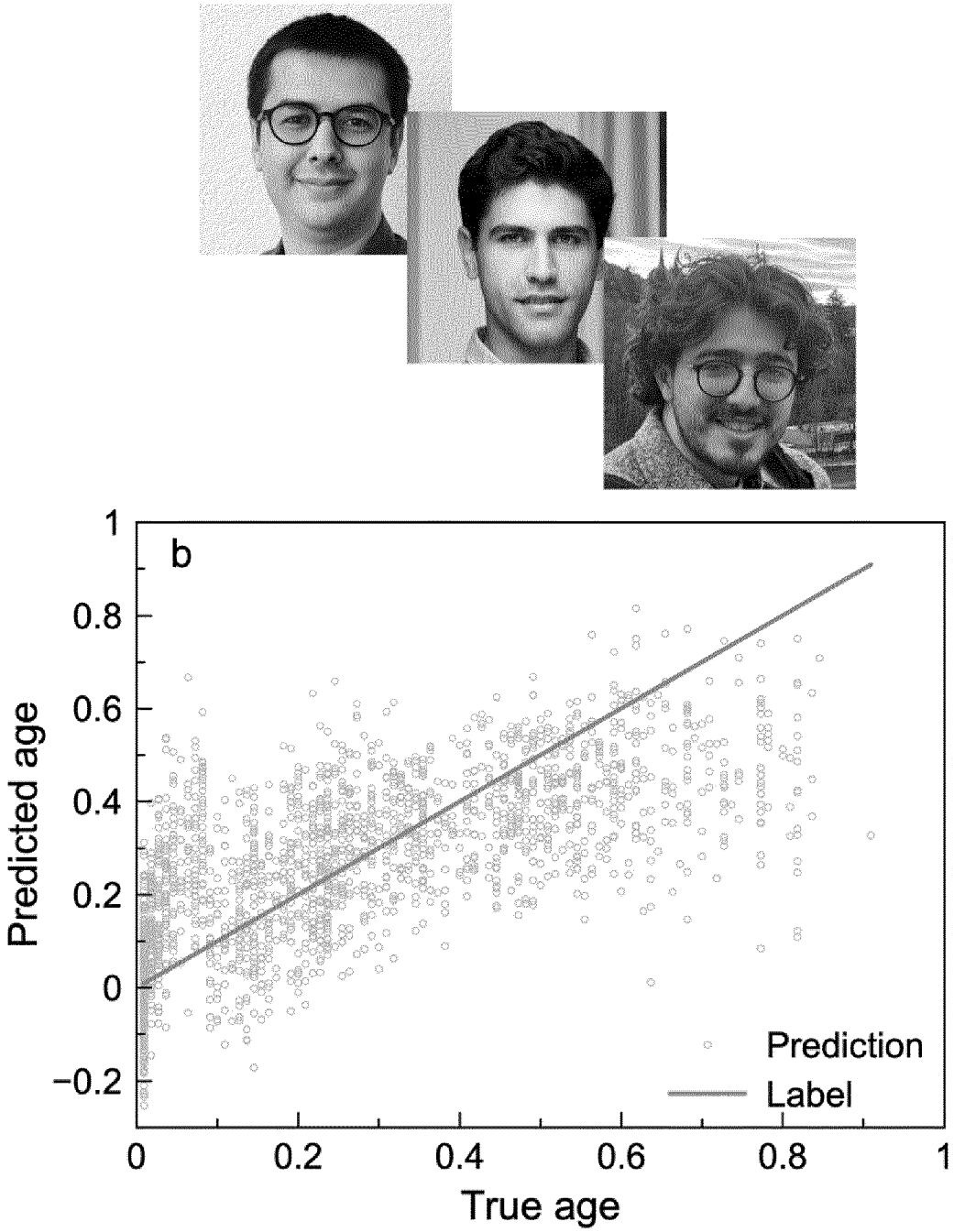
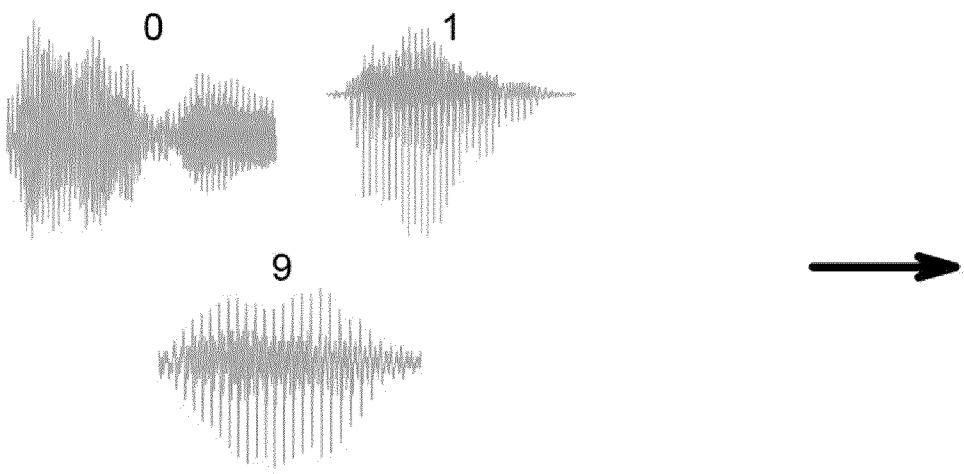

b
Predicted age
True age
Prediction
Label
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0.6
0.4
0.2
0
−0.2
0
0.2
0.4
0.6
0.8
1

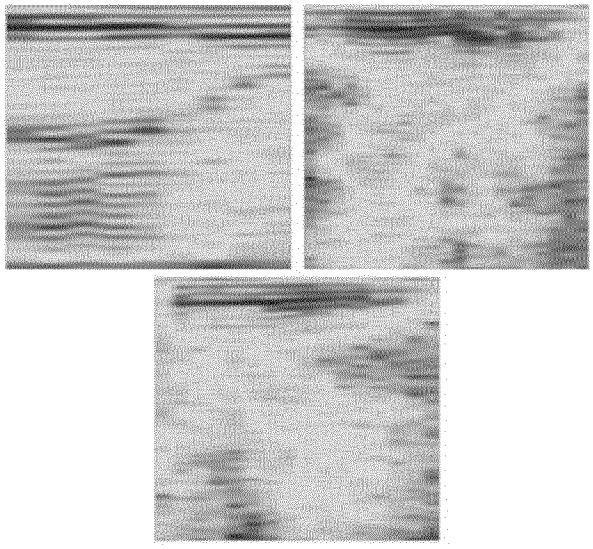
FIG. 5b



C

Predicted digits \ True digits	0	1	2	3	4	5	6	7	8	9
0	62	0	0	0	0	0	0	0	0	0
1	0	62	0	0	0	0	0	0	0	0
2	1	1	52	0	0	0	1	2	0	0
3	0	0	0	56	0	0	5	2	0	0
4	1	2	0	0	48	0	0	0	0	0
5	0	3	0	0	0	66	0	1	0	0
6	0	0	0	5	0	0	48	1	1	1
7	0	0	1	1	0	0	0	62	0	0
8	0	0	0	0	0	0	2	0	51	0
9	0	1	0	0	0	3	0	0	0	58

FIG. 5c



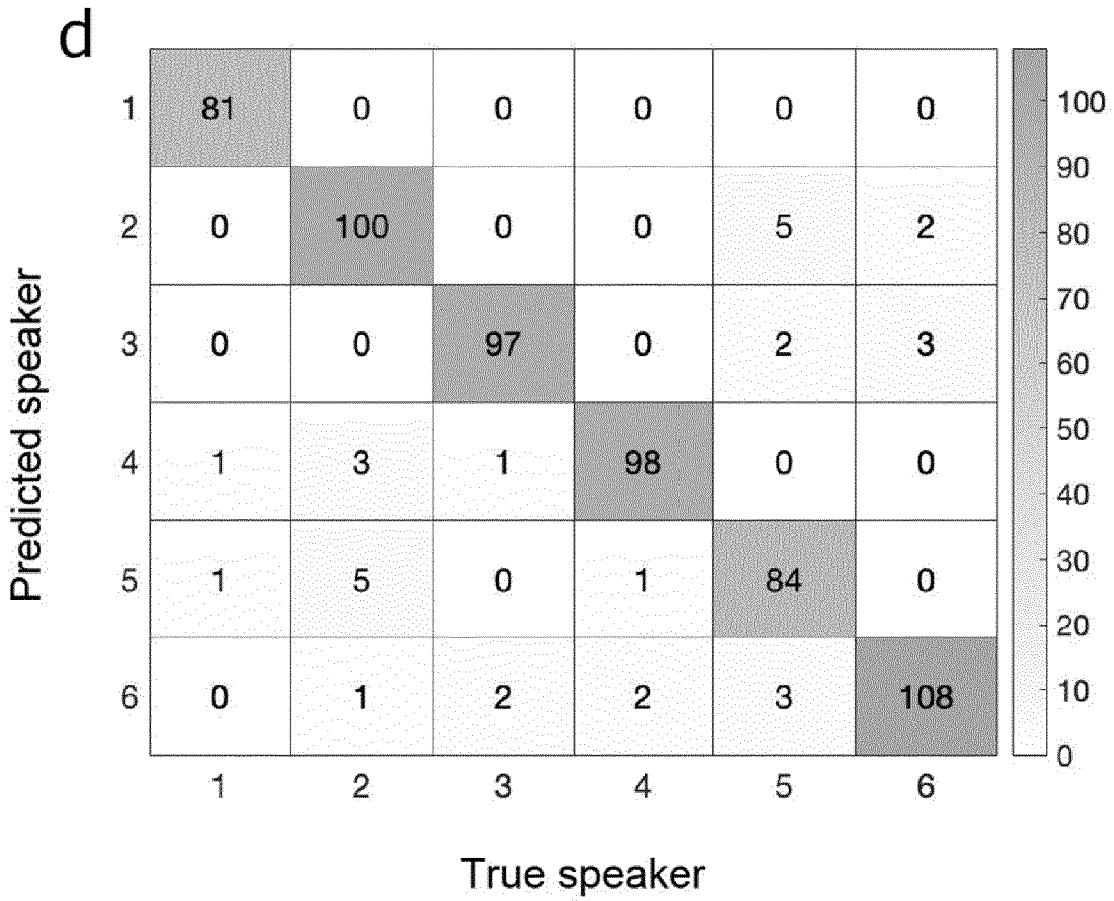

d
Predicted speaker
True speaker
1 81 0 0 0 0 0
2 0 100 0 0 5 2
3 0 0 97 0 2 3
4 1 3 1 98 0 0
5 1 5 0 1 84 0
6 0 1 2 2 3 108
1 2 3 4 5 6
100 90 80 70 60 50 40 30 20 10 0

FIG. 5d

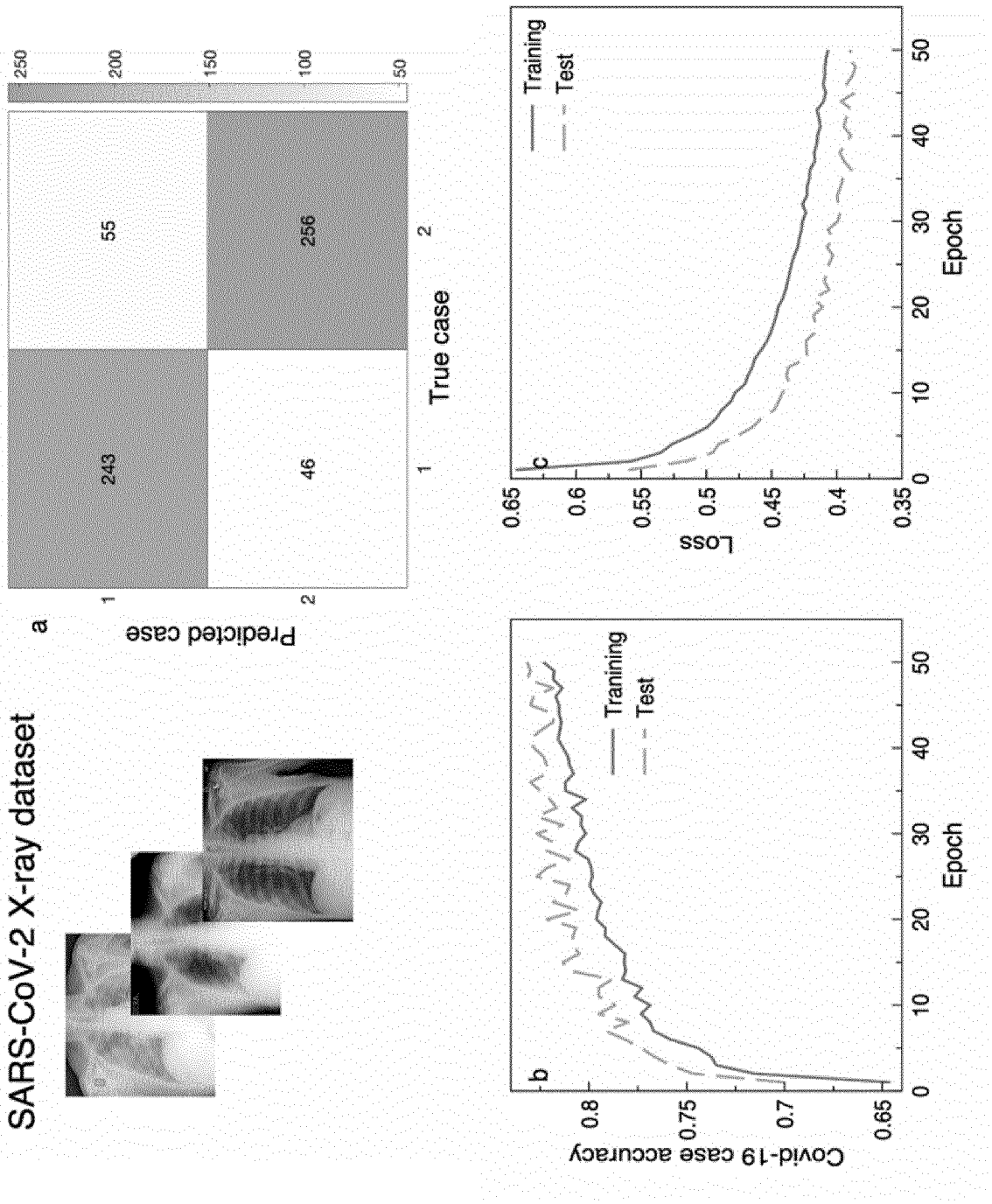

SARS-CoV-2 X-ray dataset
a
Predicted case
True case
243
46
55
256
1
2
250
200
150
100
50
b
Covid-19 case accuracy
Epoch
Tranining
Test
c
Loss
Epoch
Training
Test

FIG. 6a

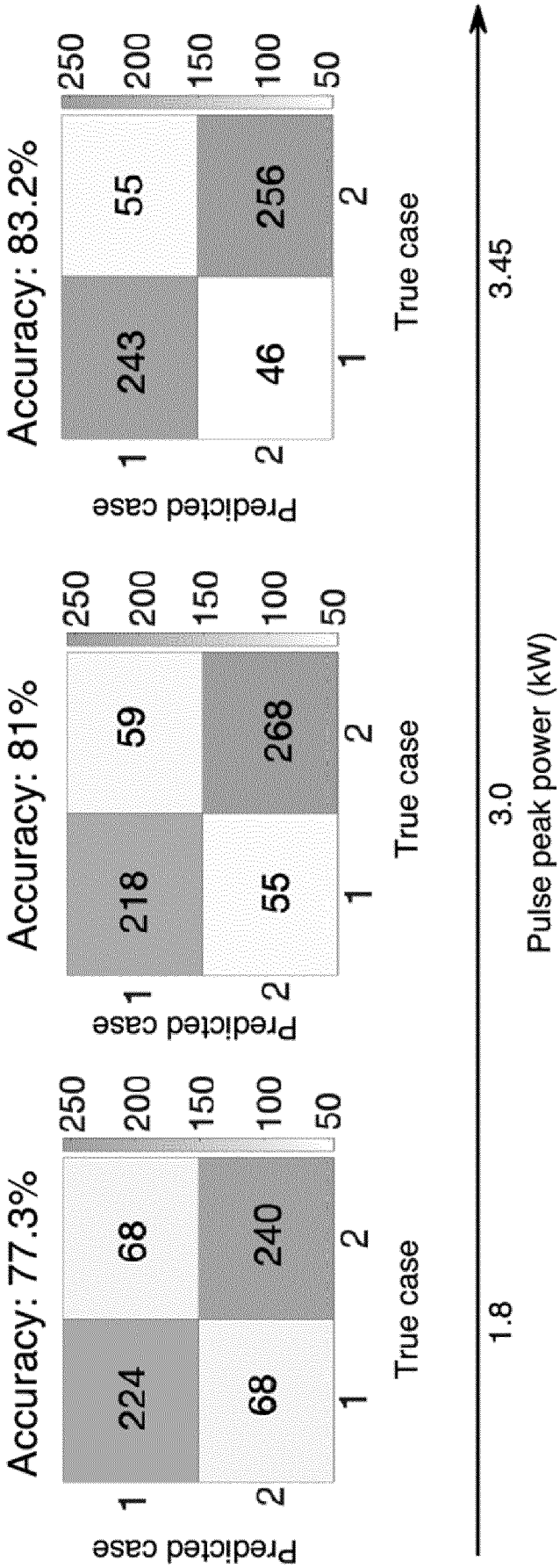

Accuracy: 77.3%
Predicted case
True case
224
68
68
240
Accuracy: 81%
218
59
55
268
Accuracy: 83.2%
243
55
46
256
1
2
50
100
150
200
250
1.8
3.0
3.45
Pulse peak power (kW)

FIG. 6b

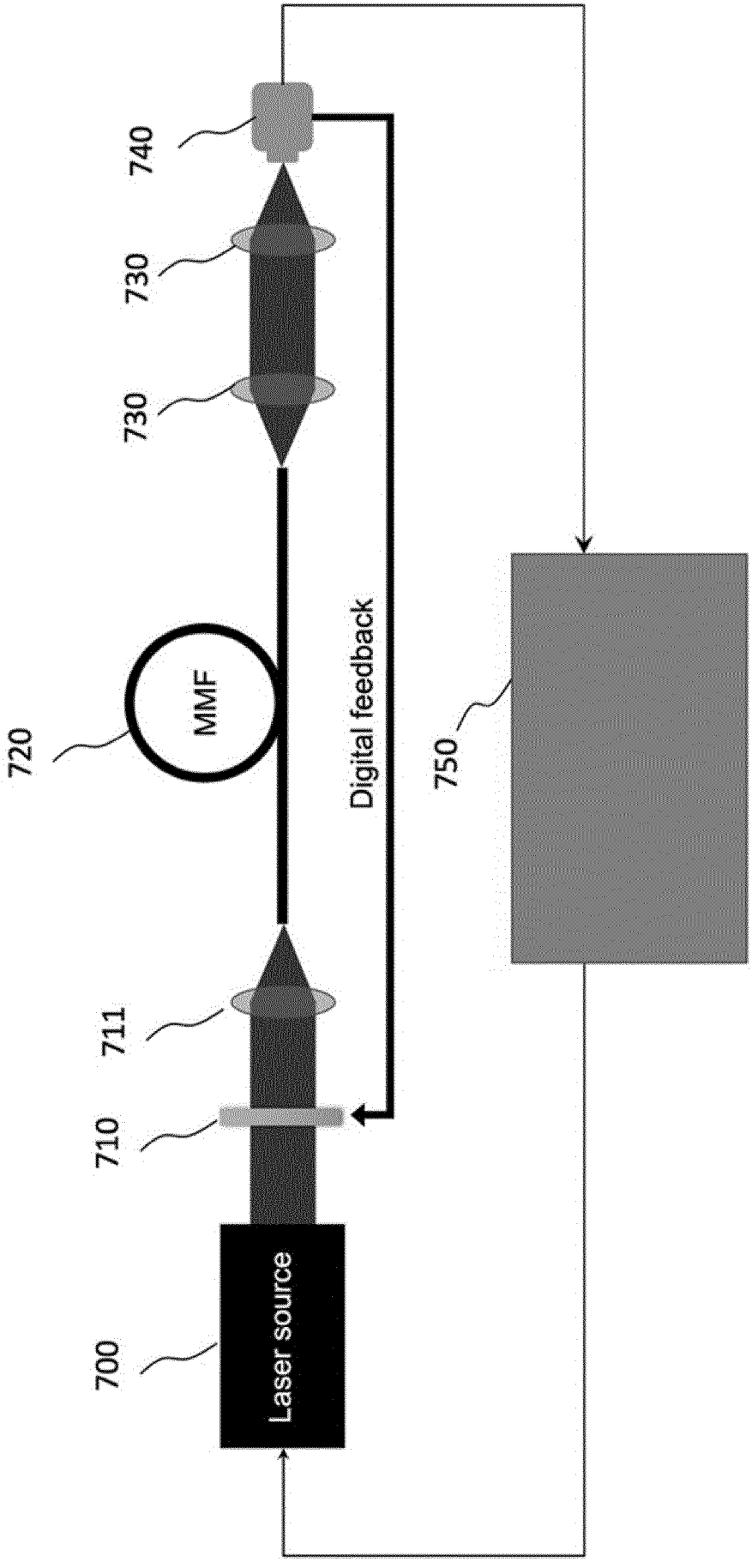

740
730
730
720
MMF
Digital feedback
750
711
710
700
Laser source

FIG. 7

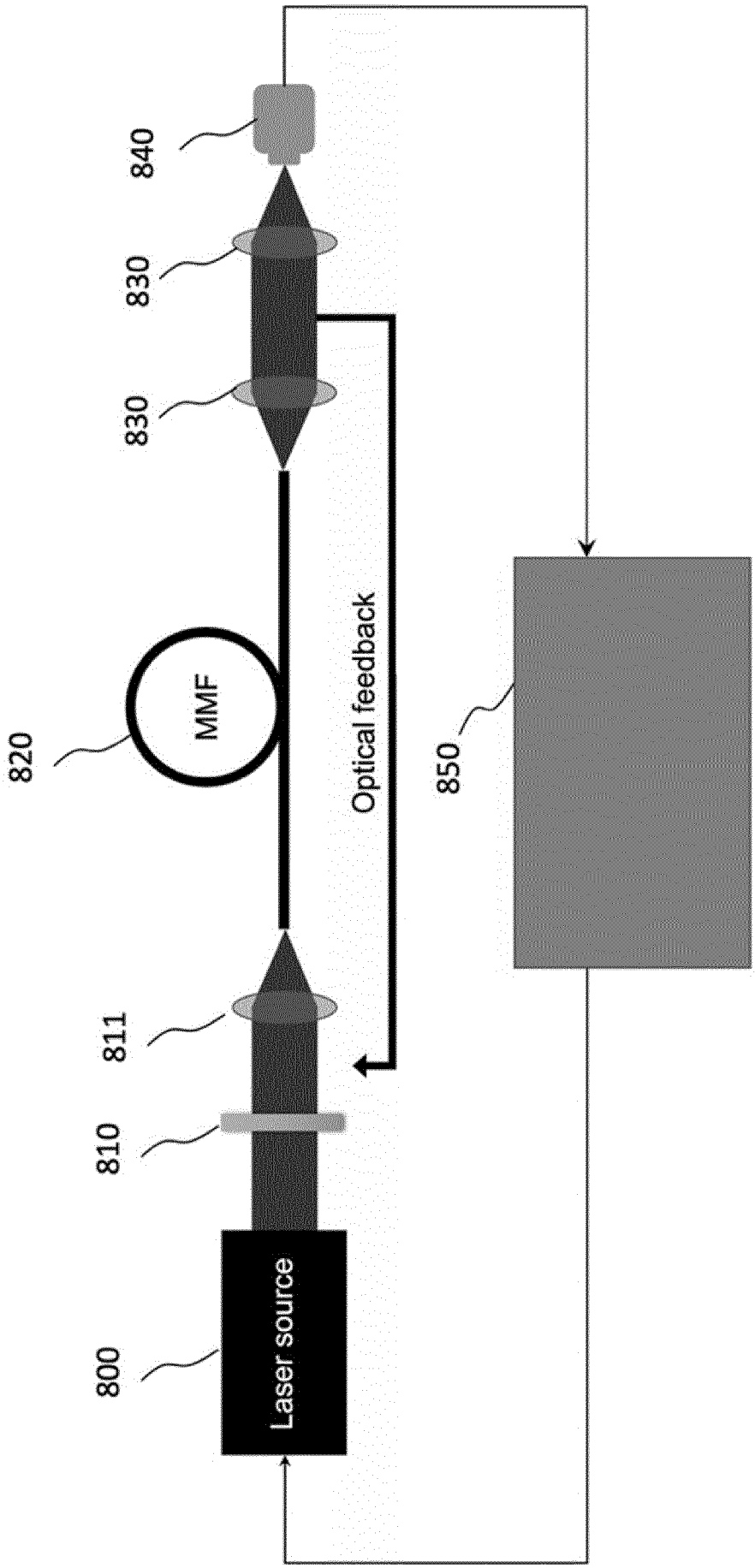

840
830
830
MMF
820
Optical feedback
850
811
810
Laser source
800

FIG. 8

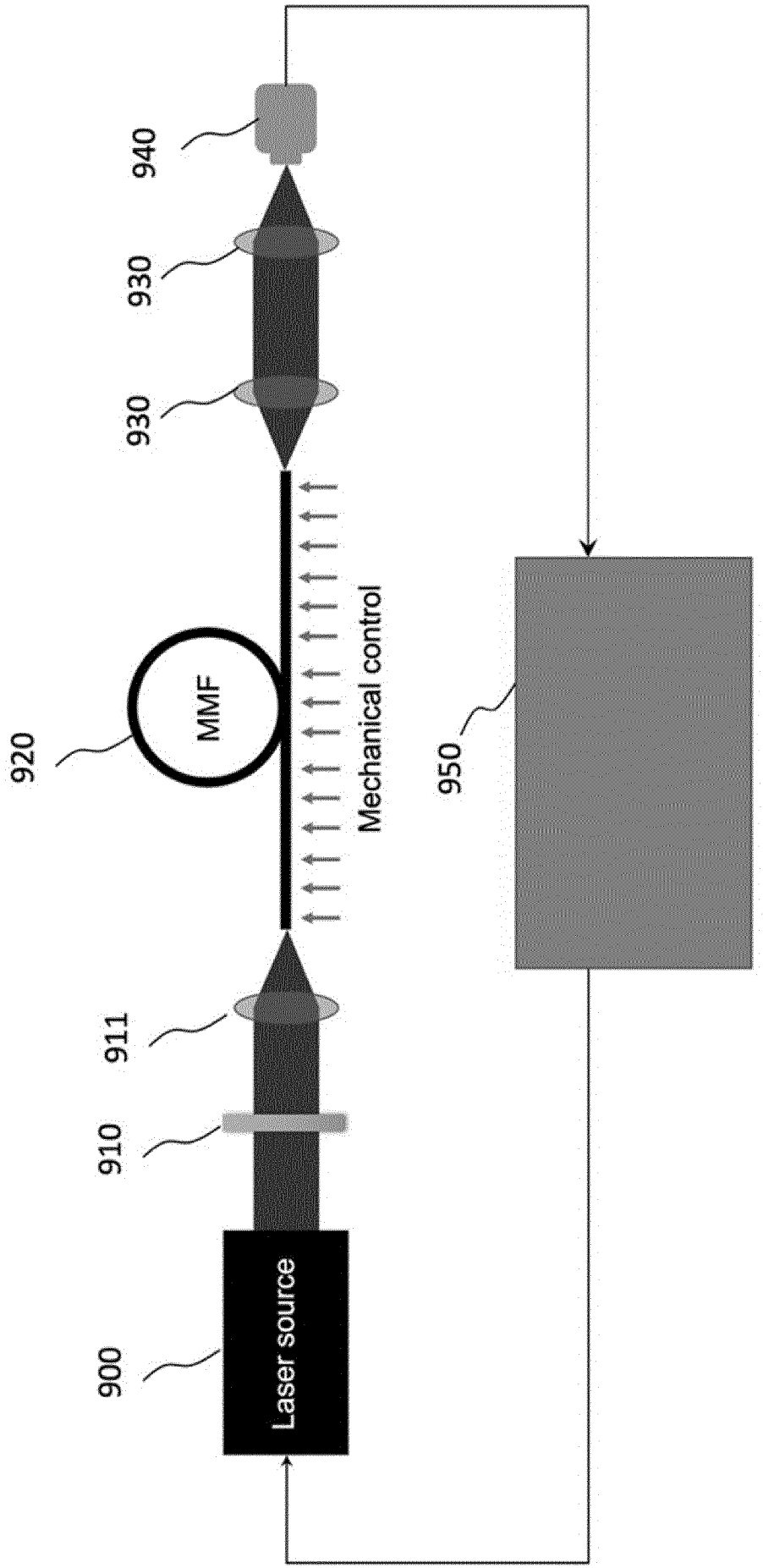

940
930
930
Mechanical control
920
MMF
950
911
910
900
Laser source

FIG. 9

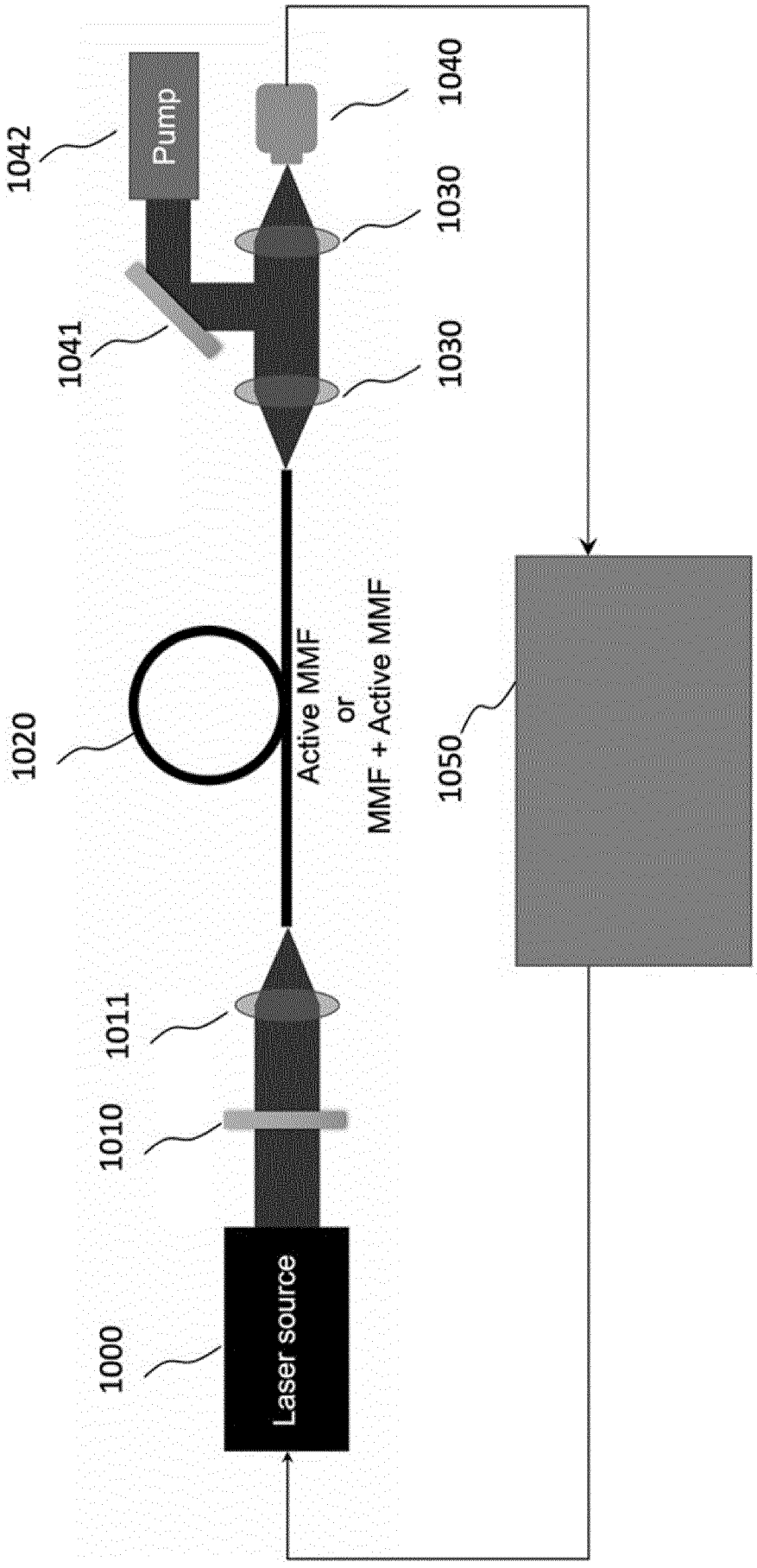

Pump
1042
1040
1030
1041
1030
1020
Active MMF
or
MMF + Active MMF
1050
1011
1010
1000
Laser source

FIG. 10

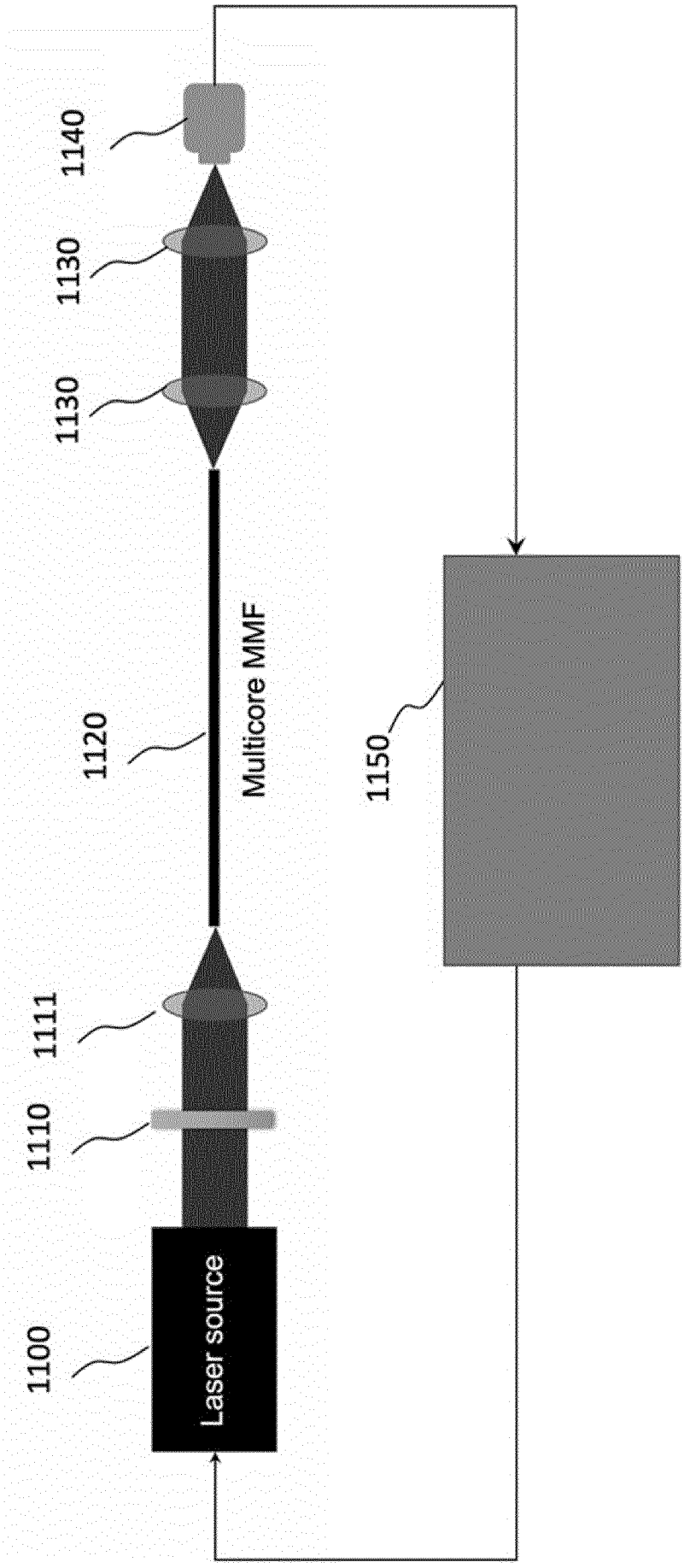

1140
1130
1130
1120
Multicore MMF
1150
1111
1110
1100
Laser source

FIG. 11

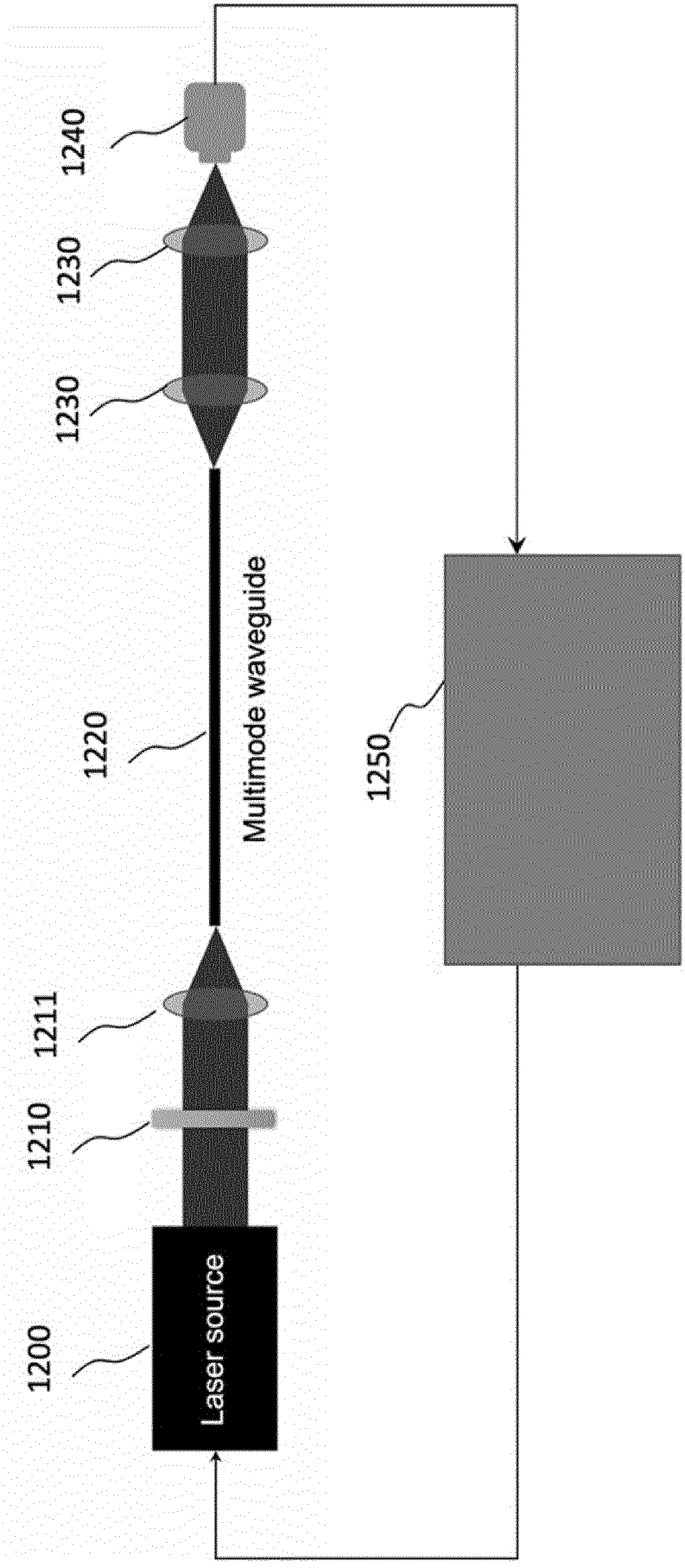

1240
1230
1230
Multimode waveguide
1220
1250
1211
1210
1200
Laser source

FIG. 12

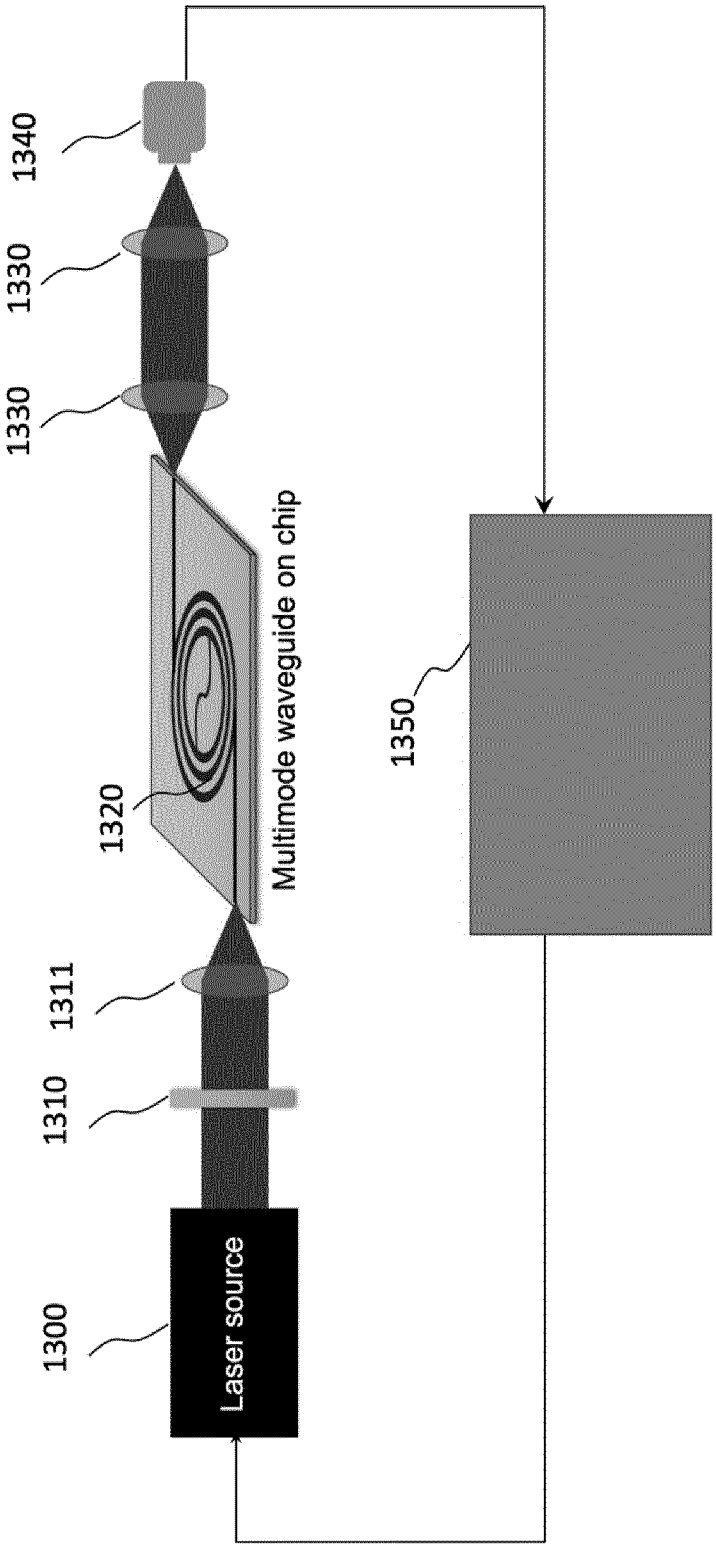

1340
1330
1330
Multimode waveguide on chip
1320
1350
1311
1310
1300
Laser source

Fig. 13

FIG. 13

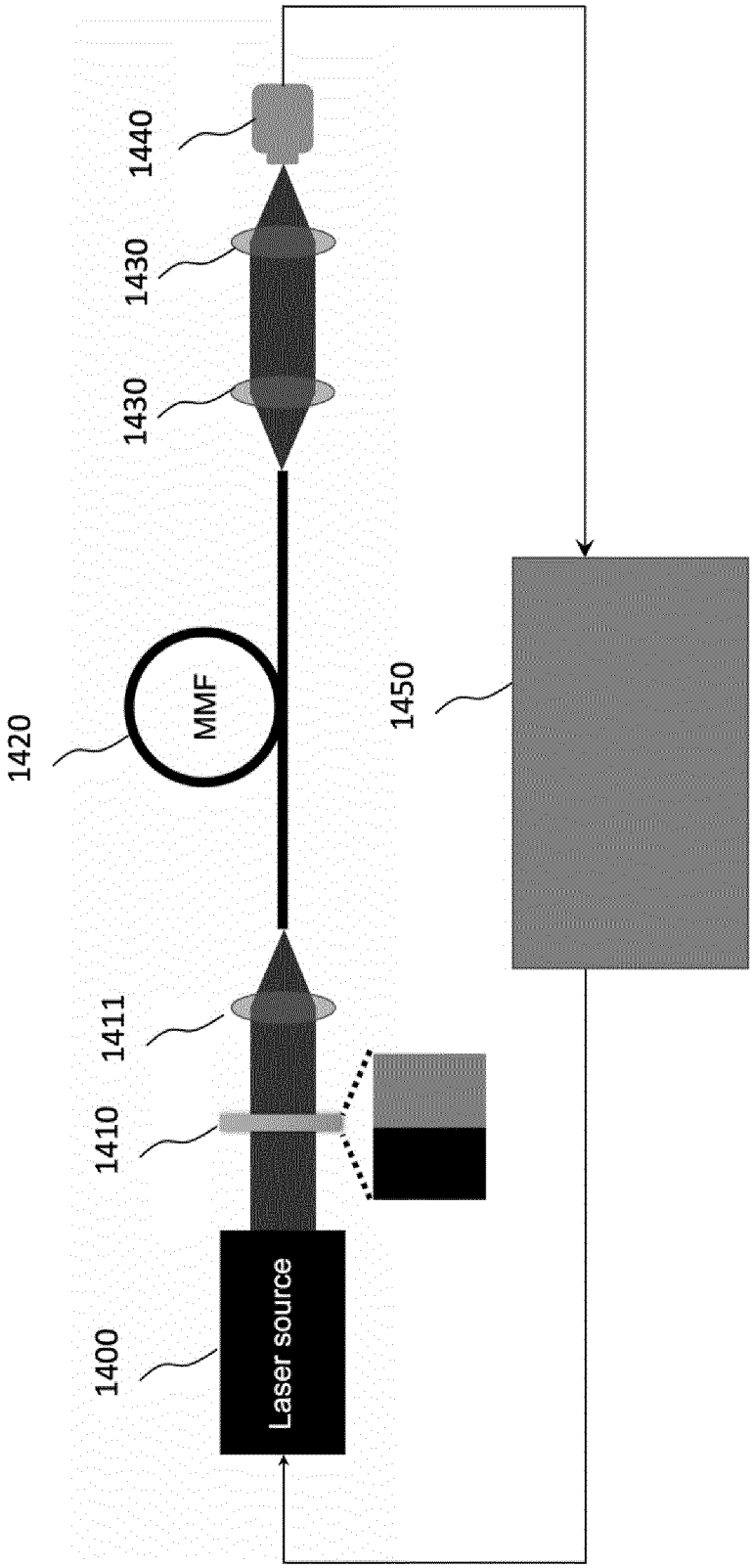


Fig. 14

FIG. 14

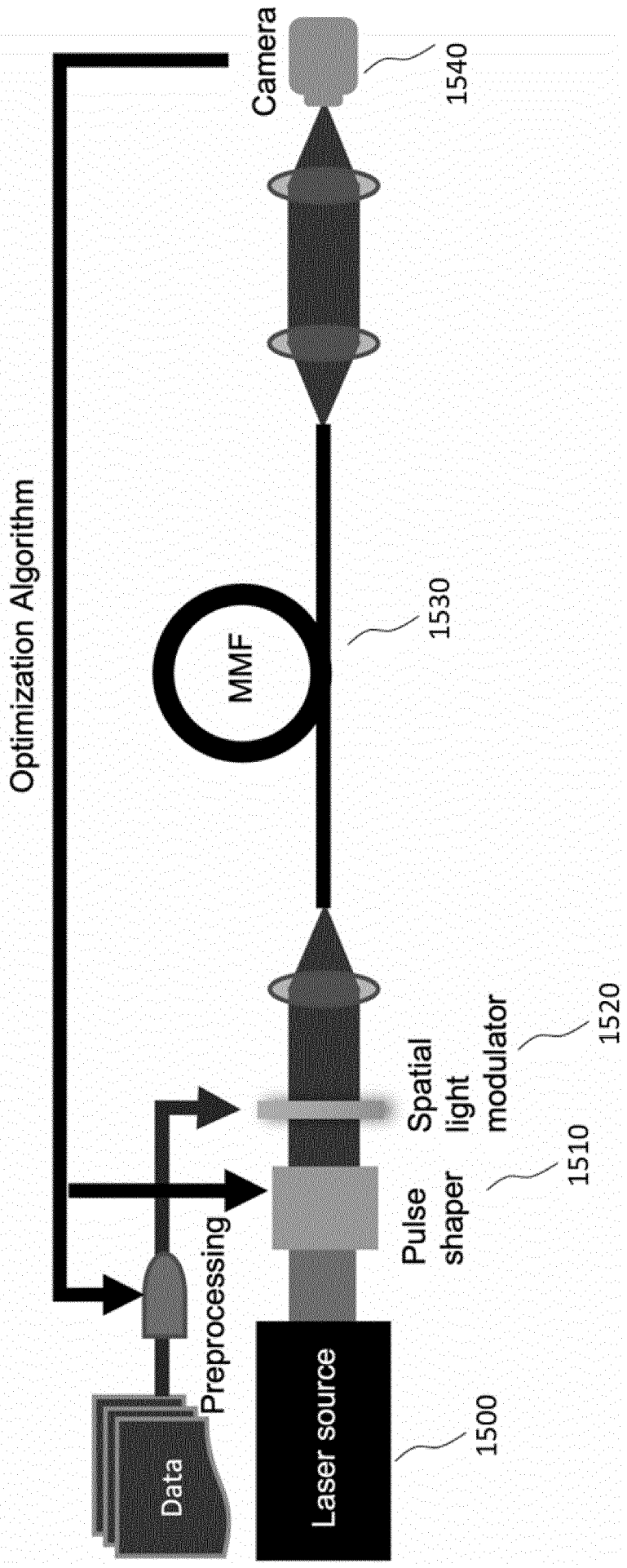

Camera
1540
Optimization Algorithm
MMF
1530
Spatial light modulator
1520
Pulse shaper
1510
Preprocessing
Data
Laser source
1500

FIG. 15

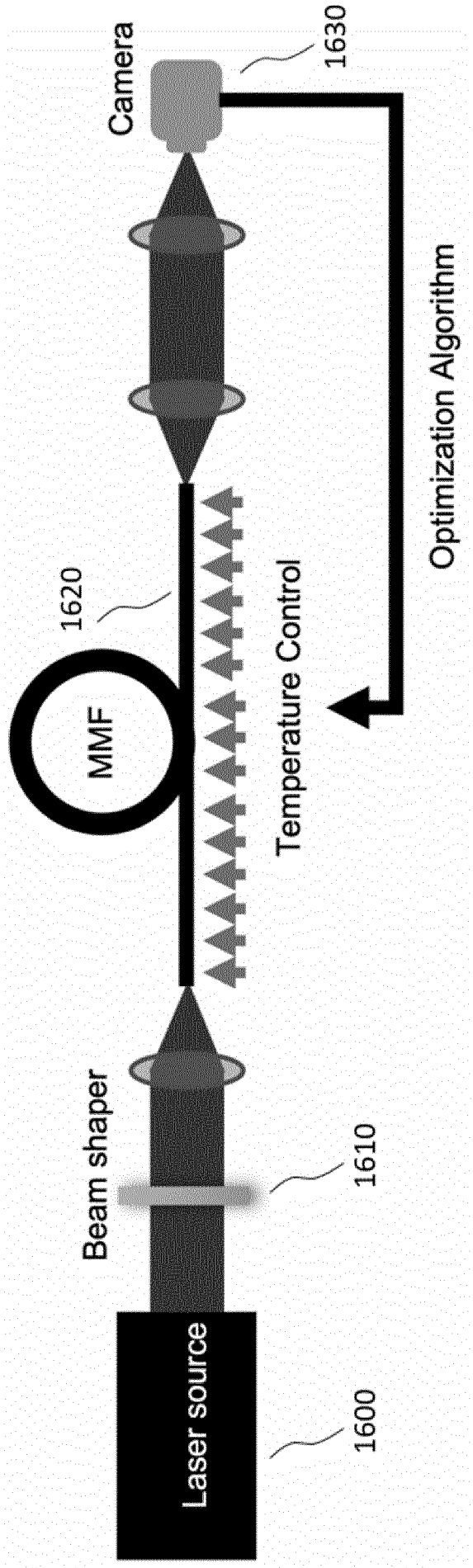

Camera
1630
Optimization Algorithm
1620
MMF
Temperature Control
Beam shaper
1610
Laser source
1600

FIG. 16

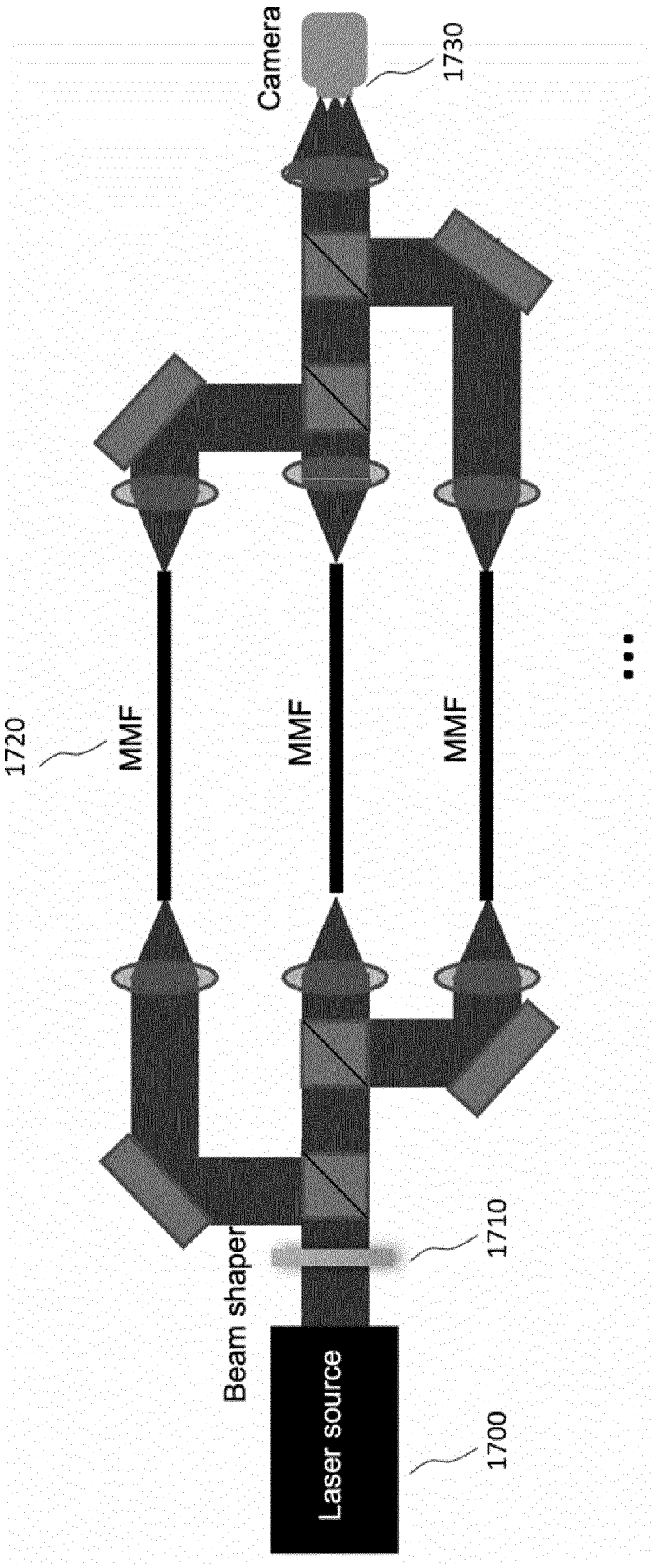

Camera
1730
1720
MMF
MMF
MMF
Beam shaper
1710
Laser source
1700

FIG. 17

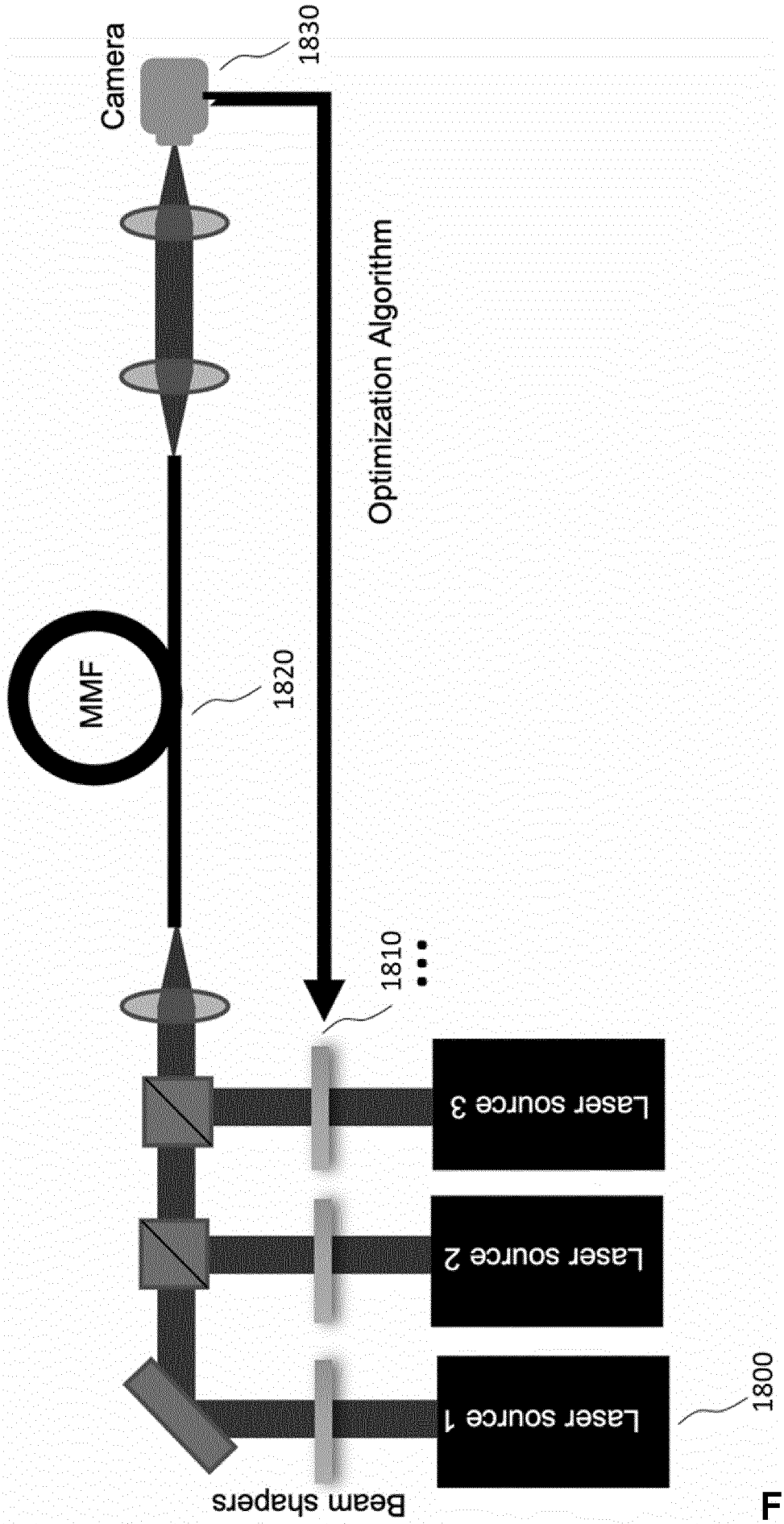

Camera
1830
Optimization Algorithm
MMF
1820
1810
Laser source 3
Laser source 2
Laser source 1
1800
Beam shapers

FIG. 18

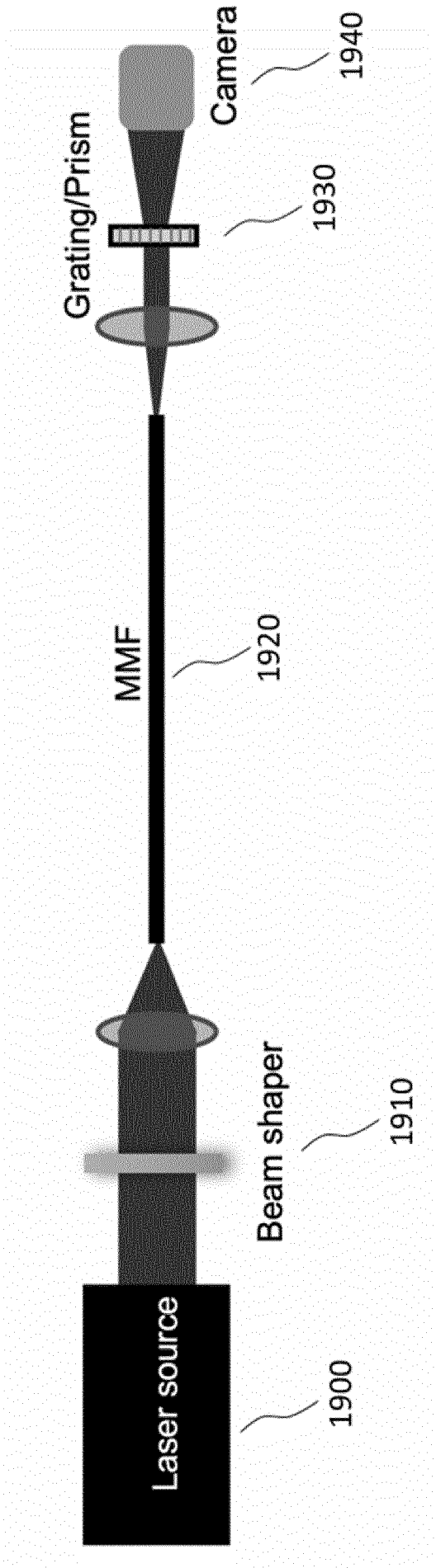

Camera
1940
Grating/Prism
1930
MMF
1920
Beam shaper
1910
Laser source
1900

FIG. 19

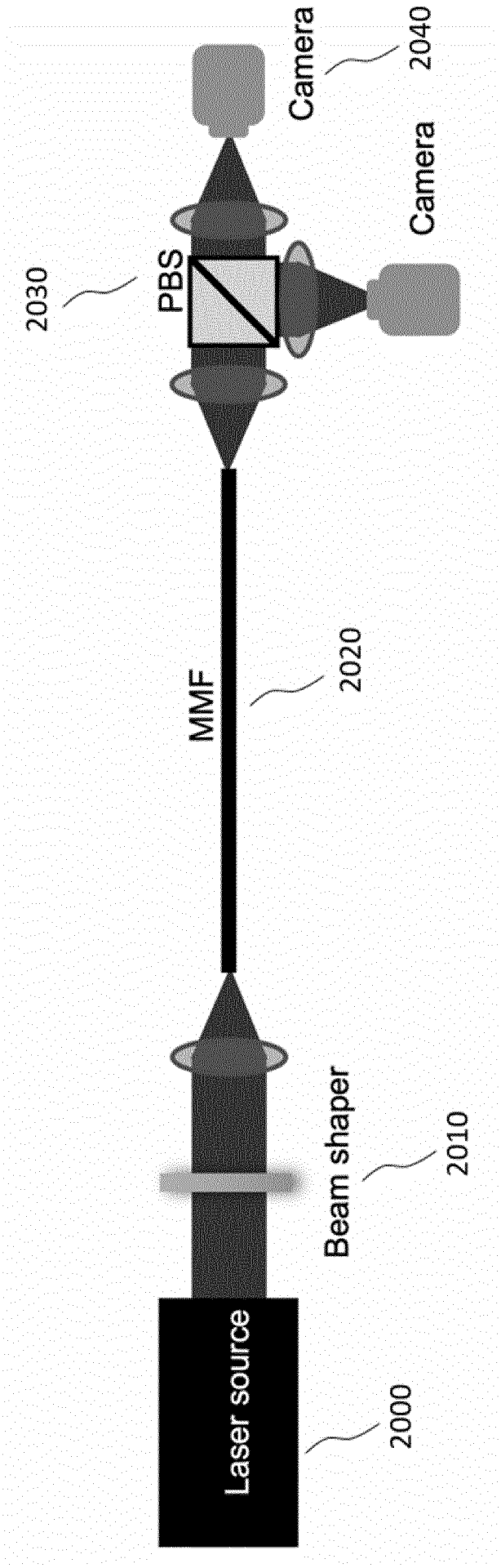

Camera
2040
Camera
PBS
2030
MMF
2020
Beam shaper
2010
Laser source
2000

FIG. 20

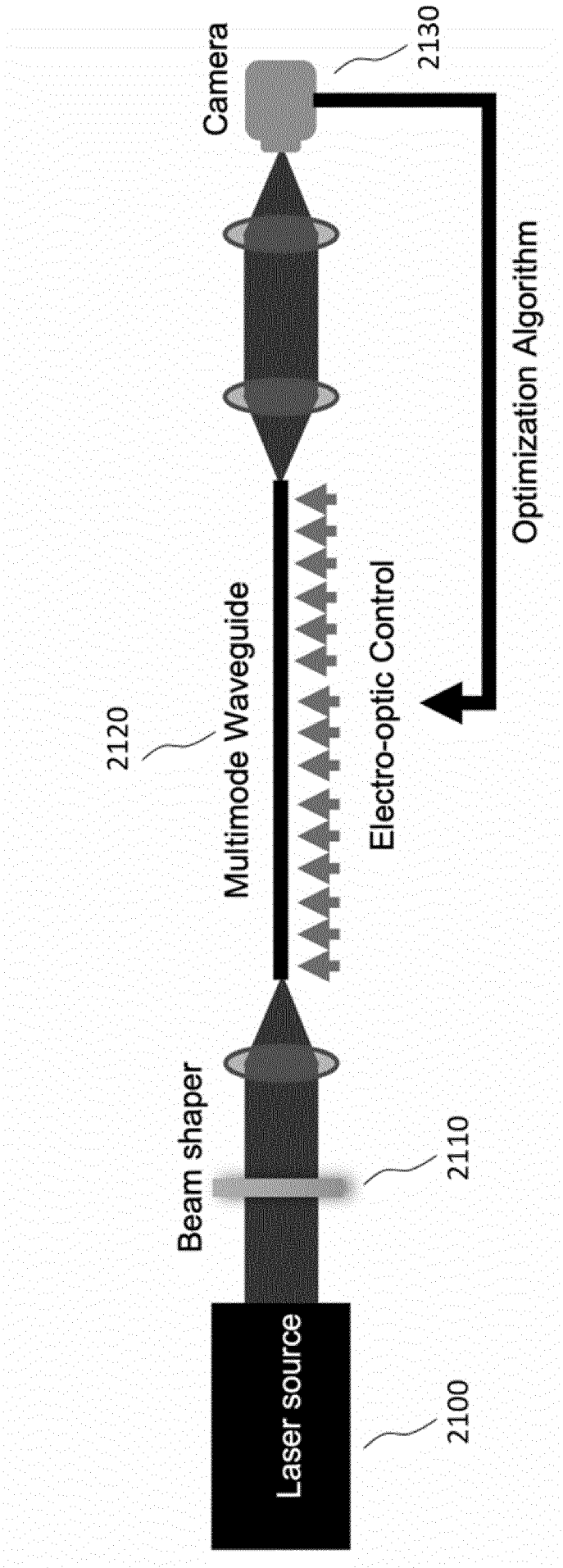

Camera
2130
Optimization Algorithm
Electro-optic Control
2120
Multimode Waveguide
Beam shaper
2110
Laser source
2100

FIG. 21

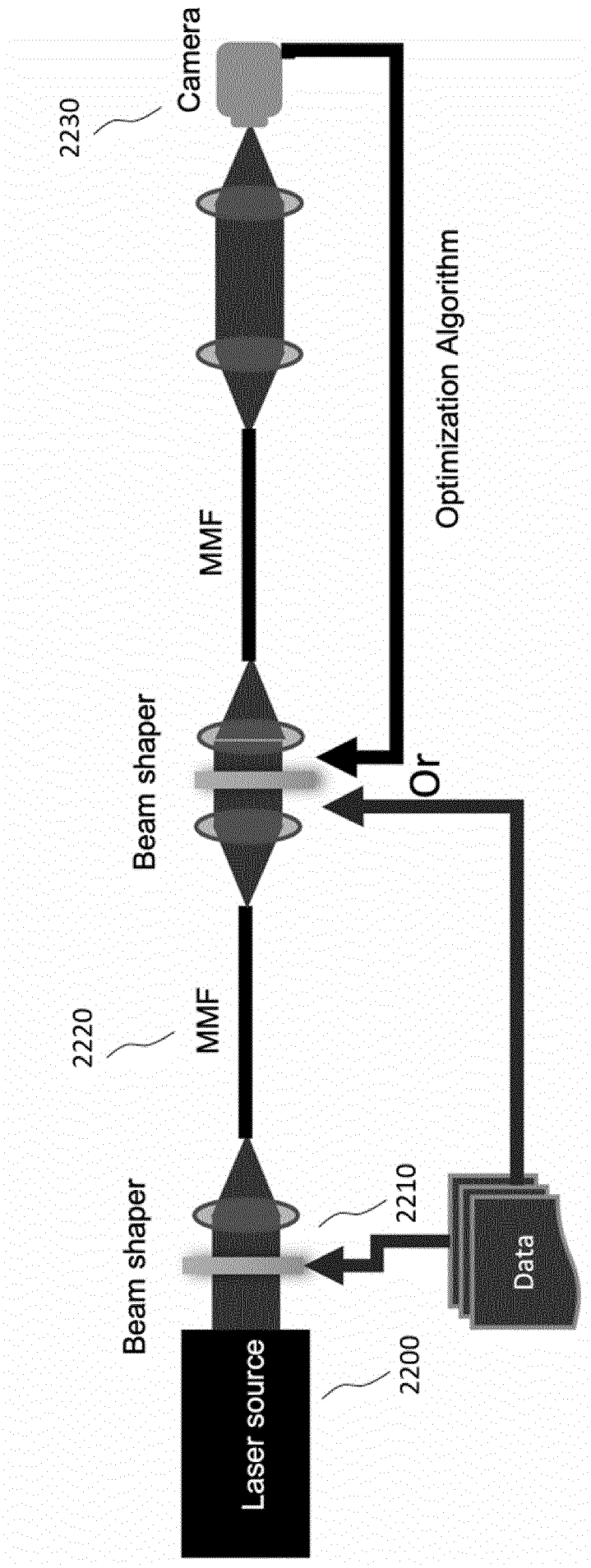

Camera
2230
MMF
Optimization Algorithm
Beam shaper
Or
2220
MMF
Beam shaper
2210
Data
Laser source
2200

FIG. 22

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/086406

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06N3/067
ADD. G06N3/04 G06N3/08

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)
G06N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SHACHAR RESISI ET AL: "Wavefront shaping in multimode fibers by transmission matrix engineering", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 7 October 2019 (2019-10-07), XP081511584, the whole document ----- US 10 627 849 B1 (AEROSPACE CORP [US]) 21 April 2020 (2020-04-21) column 3, line 25 - column 11, line 41; figures 3A-3B ----- -/--	1-88
A		1-88

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 April 2022	21/04/2022

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Suarez Y Gonzalez, R

1

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/086406

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2017/351293 A1 (CAROLAN JACQUES JOHANNES [US] ET AL) 7 December 2017 (2017-12-07) paragraphs [0032] - [0066]; figures 1-3,4B paragraphs [0071] - [0077]; figures 9-10	1-88
A	KITAYAMA KEN-ICHI ET AL: "Novel frontier of photonics for data processing-Photonic accelerator", APL PHOTONICS, AMERICAN INSTITUTE OF PHYSICS, 2 HUNTINGTON QUADRANGLE, MELVILLE, NY 11747, vol. 4, no. 9, 24 September 2019 (2019-09-24), XP012241580, DOI: 10.1063/1.5108912 [retrieved on 2019-09-24] Section III; page 4 - page 20	1-88

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2021/086406

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		KR 20190015732 A	14-02-2019
		US 2017351293 A1	07-12-2017
		US 2019294199 A1	26-09-2019
		US 2020379504 A1	03-12-2020
		WO 2017210550 A1	07-12-2017