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(54) **OPTOELECTRONIC DEVICE WITH A PHOTONIC INTERPOSER FOR CHIPLET INTERCONNECTS**

(71) Applicant: **National University of Singapore**, Singapore (SG)

(72) Inventors: **Zefeng XU**, Singapore (SG); **Chun-Kuei CHEN**, Singapore (SG); **Aaron Voon-Yew THEAN**, Singapore (SG)

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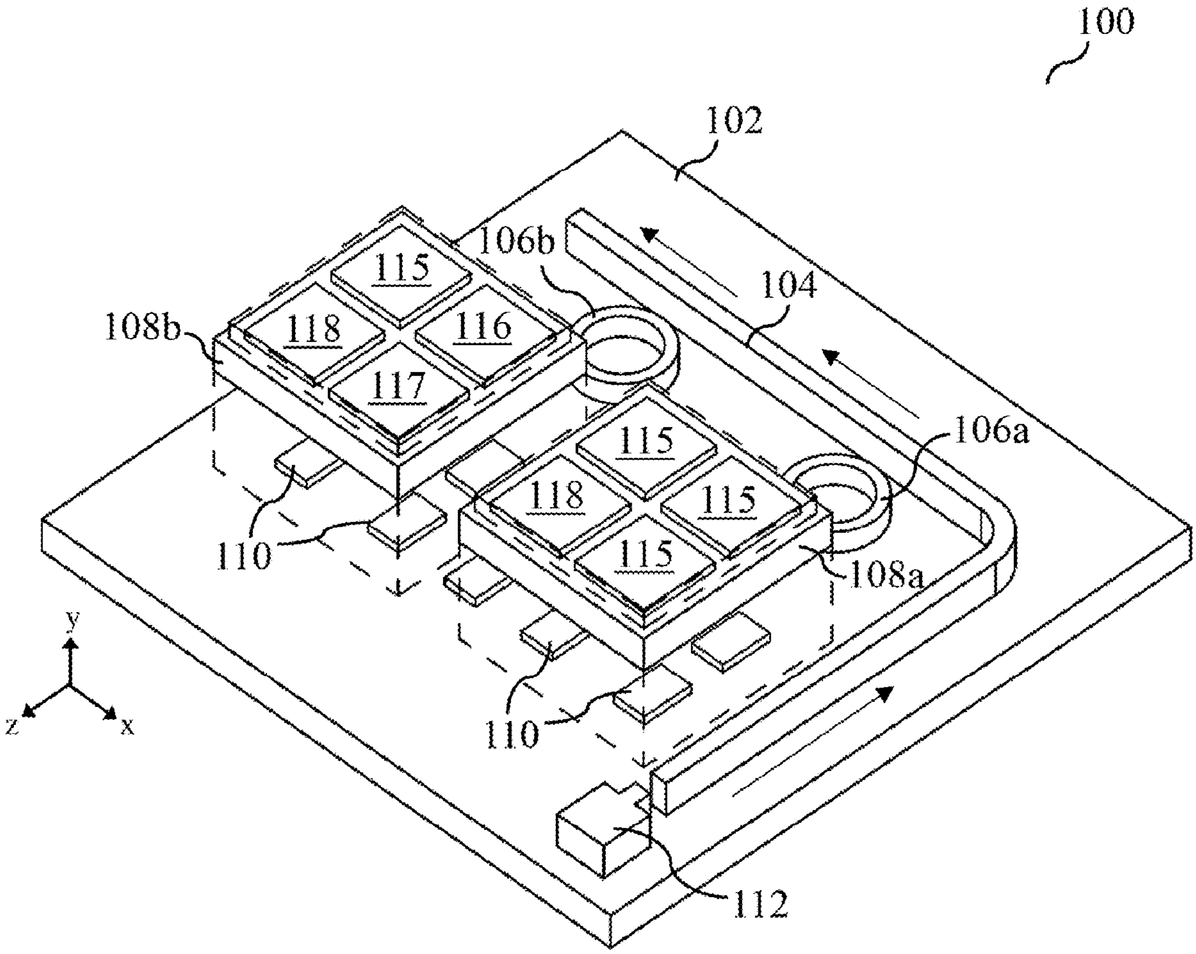
(57) **ABSTRACT**

This document describes an optoelectronic device comprising a photonic interposer that is provided with a plurality of chiplets and a multimode waveguide. Each of the plurality of chiplets are communicatively connected to a micro-ring resonator router that is provided adjacent to each chiplet, and each micro-ring resonator router is electromagnetically coupled to the multimode waveguide such that each of the micro-ring resonators are able to selectively couple optical signals propagating in the multimode waveguide



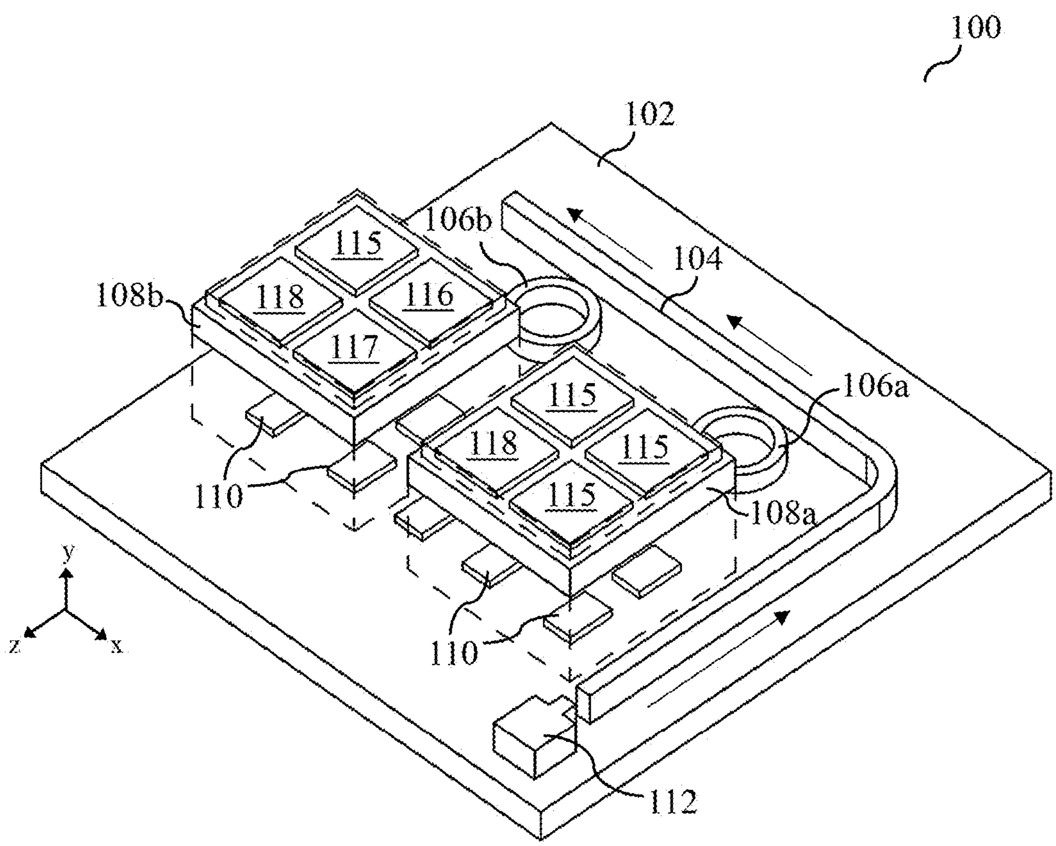


FIGURE 1

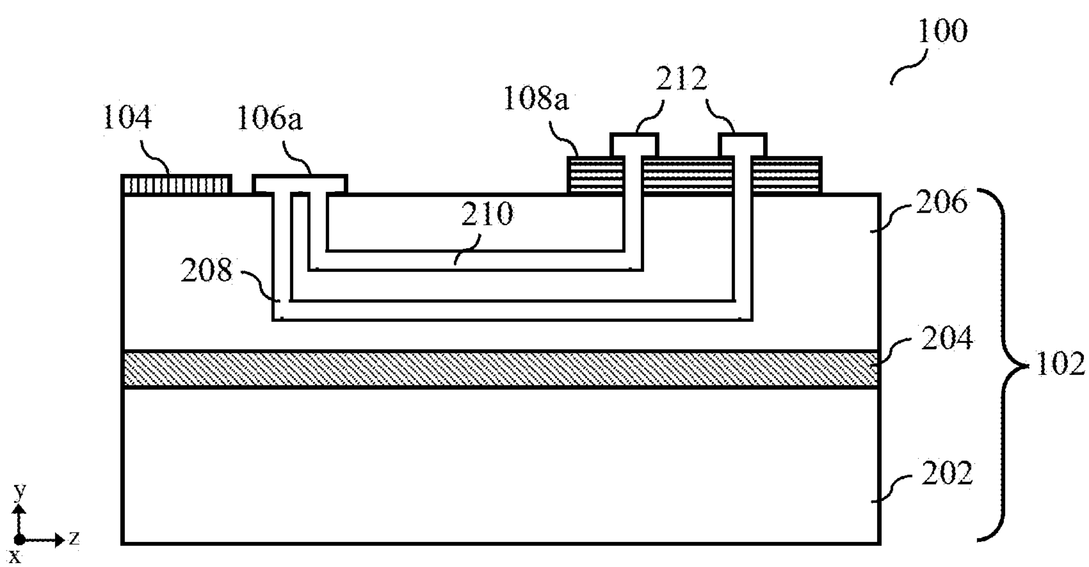


FIGURE 2

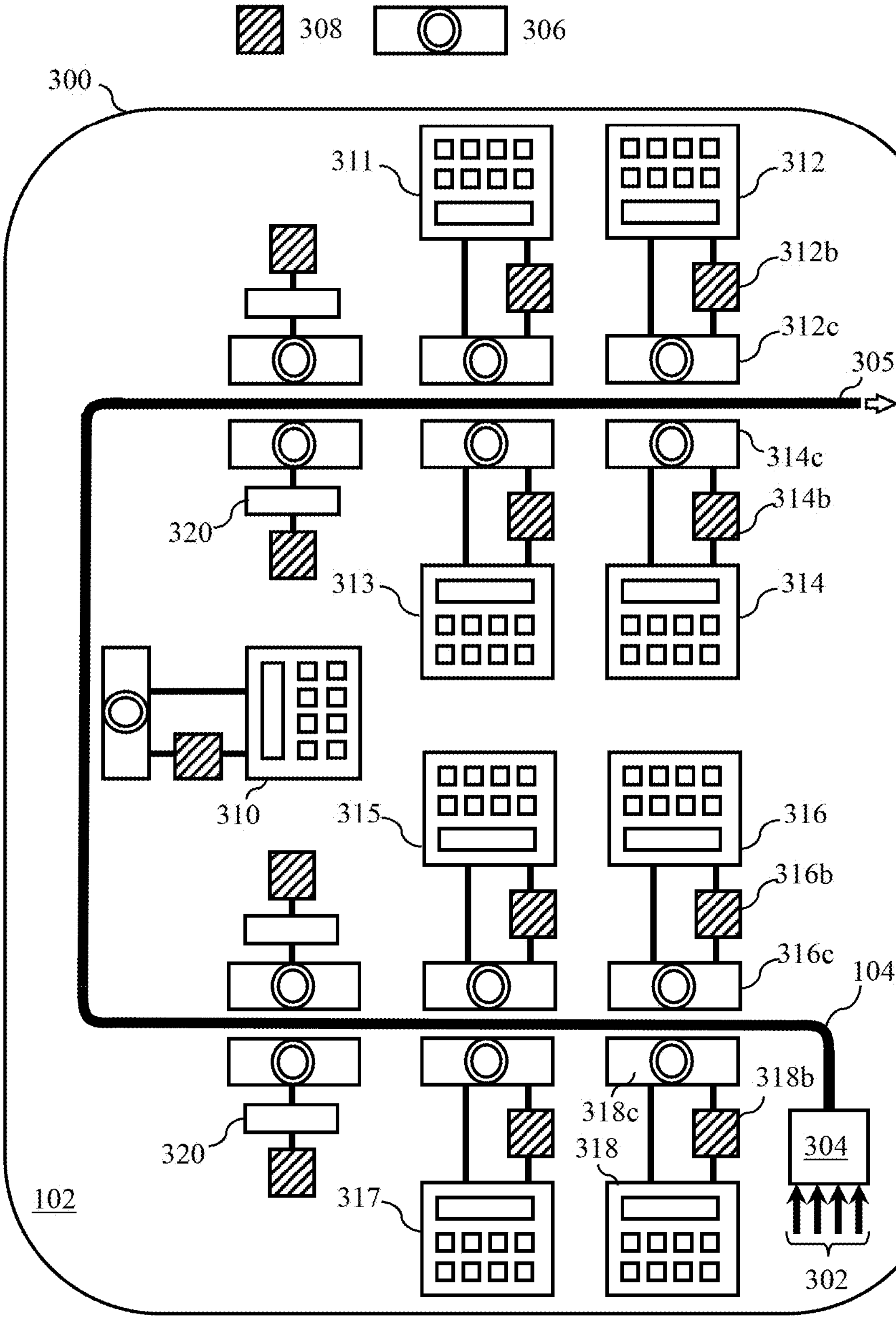

308
306
300
311
312
312b
312c
305
314c
314b
320
313
314
310
315
316
316b
316c
104
318b
318c
318
304
320
317
102
302

FIGURE 3

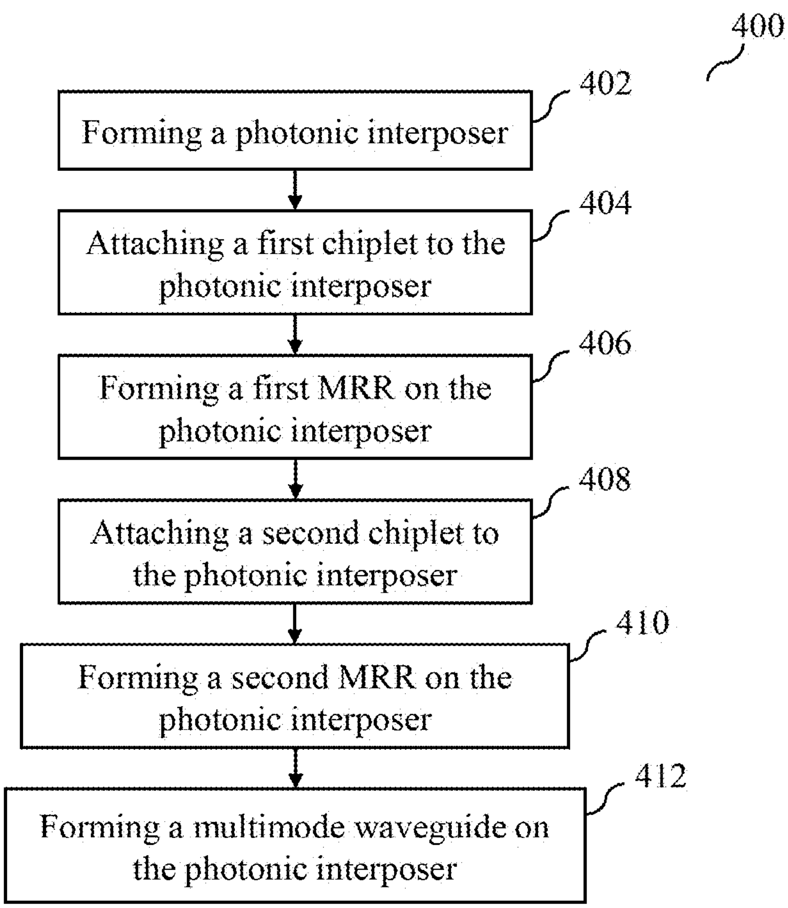

400
402
Forming a photonic interposer
404
Attaching a first chiplet to the photonic interposer
406
Forming a first MRR on the photonic interposer
408
Attaching a second chiplet to the photonic interposer
410
Forming a second MRR on the photonic interposer
412
Forming a multimode waveguide on the photonic interposer

FIGURE 4

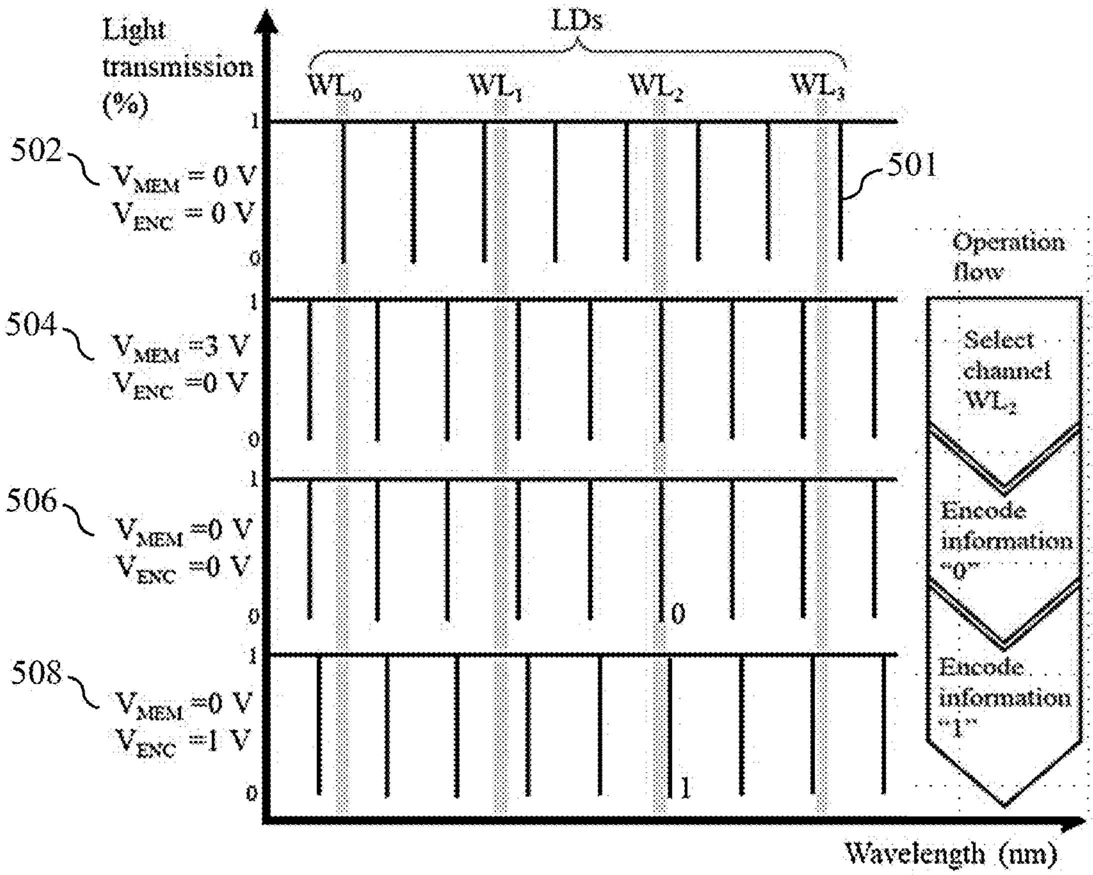

Light transmission (%)
LDs
WL0
WL1
WL2
WL3
1
0
502
VMEM = 0 V
VENC = 0 V
501
504
VMEM =3 V
VENC =0 V
506
VMEM =0 V
VENC =0 V
0
508
VMEM =0 V
VENC =1 V
1
Operation flow
Select channel WL2
Encode information "0"
Encode information "1"
Wavelength (nm)

FIGURE 5

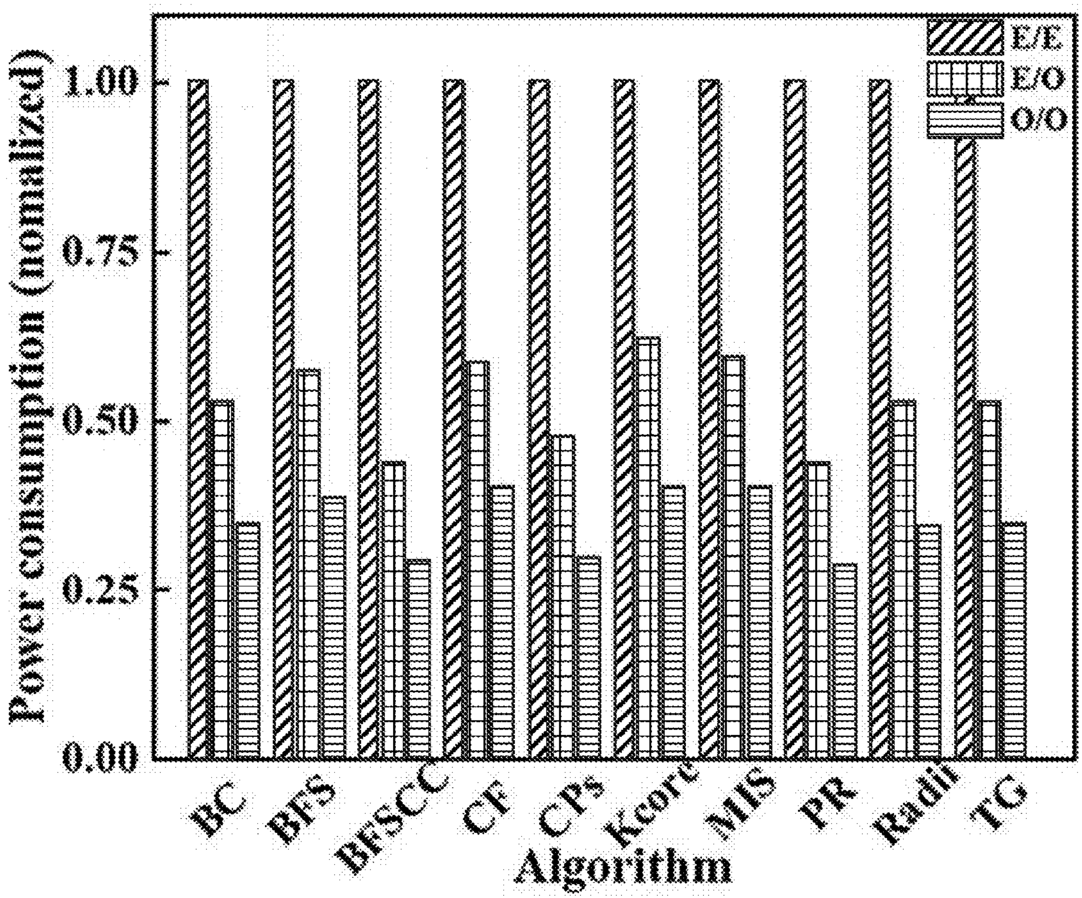

Power consumption (nomalized)
1.00
0.75
0.50
0.25
0.00
E/E
E/O
O/O
BC
BFS
BFSCC
CF
CPs
Kcore
MIS
PR
Radii
TG
Algorithm

FIGURE 6a

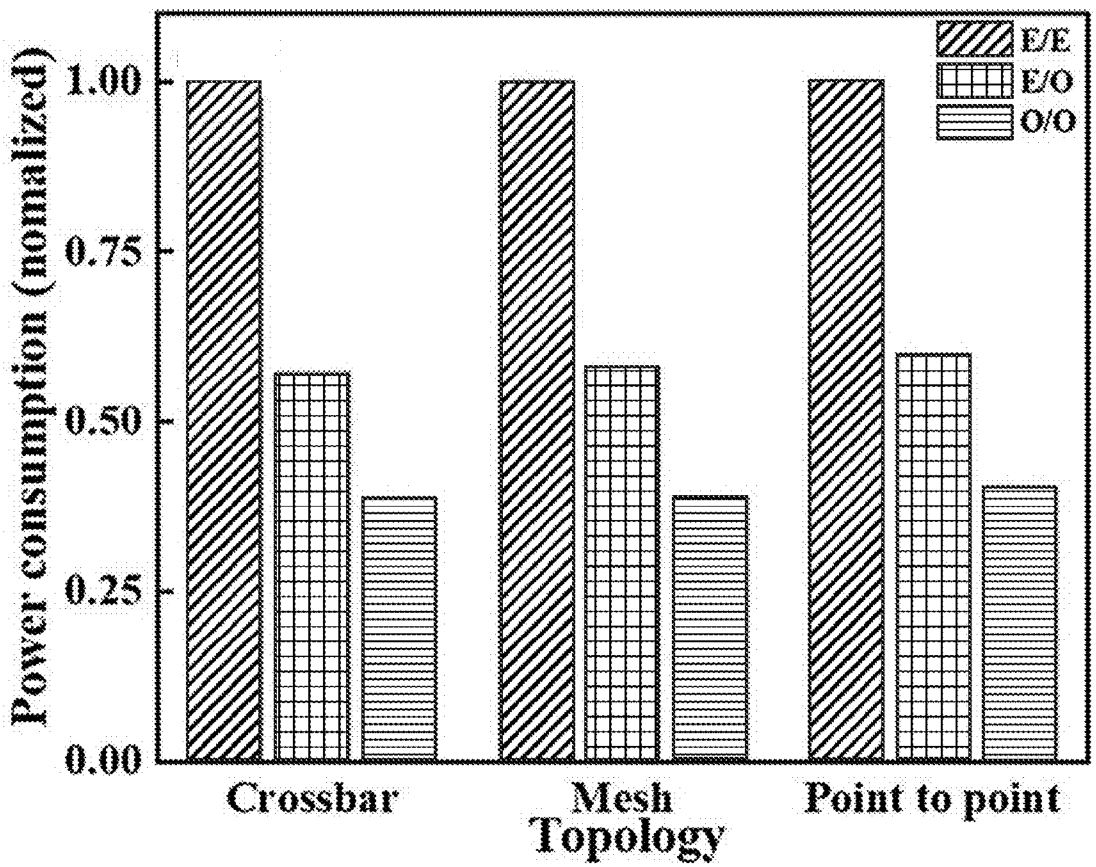

Power consumption (nomalized)
1.00
0.75
0.50
0.25
0.00
E/E
E/O
O/O
Crossbar
Mesh
Point to point
Topology

FIGURE 6b

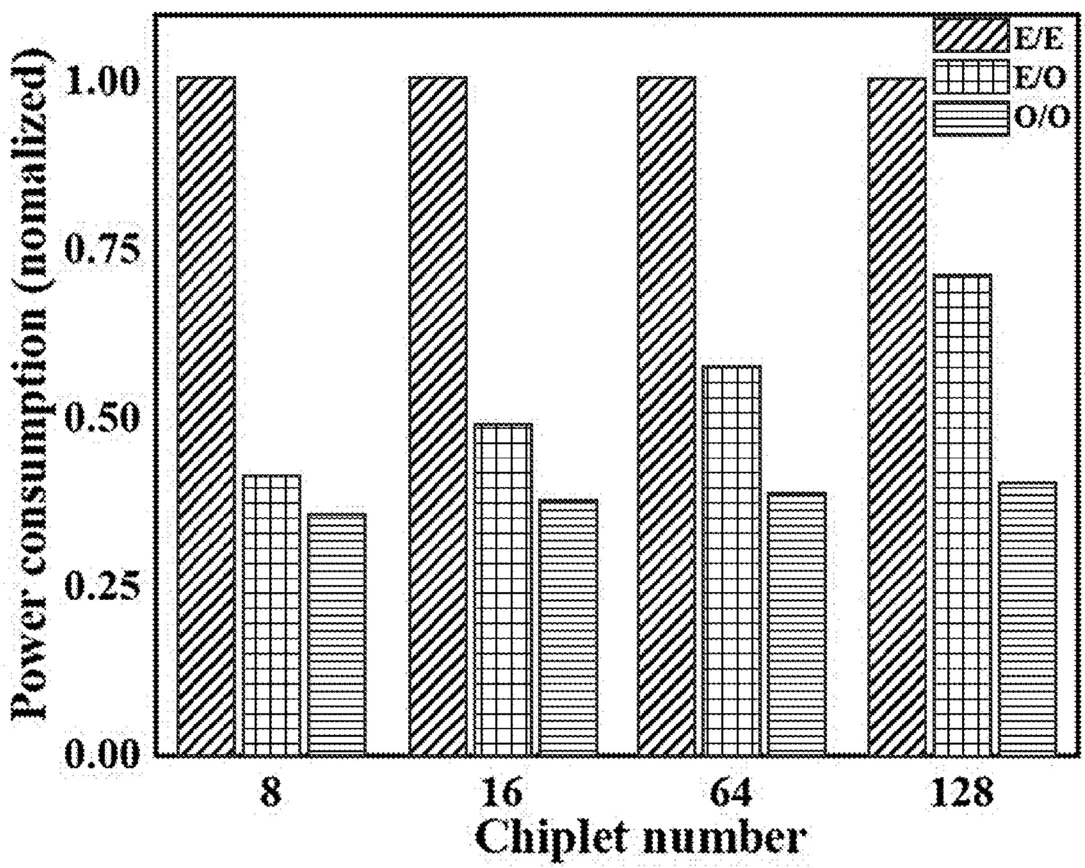

E/E
E/O
O/O
Power consumption (nomalized)
1.00
0.75
0.50
0.25
0.00
8
16
64
128
Chiplet number

FIGURE 6c

OPTOELECTRONIC DEVICE WITH A PHOTONIC INTERPOSER FOR CHIPLET INTERCONNECTS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority to Singapore patent application no. 10202302560X which was filed on 12 Sep. 2023, the contents of which are hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] This application relates to an optoelectronic device comprising a photonic interposer that is provided with a plurality of chiplets and a multimode waveguide. Each of the plurality of chiplets are communicatively connected to a micro-ring resonator router that is provided adjacent to each chiplet, and each micro-ring resonator router is electromagnetically coupled to the multimode waveguide such that each of the micro-ring resonators are able to selectively couple optical signals propagating in the multimode waveguide.

BACKGROUND

[0003] Chiplet technology involves the creation of smaller, specialized modular chips (chiplets) that may be interconnected to form a complete system. Through the use of such chiplets, large integrated circuits may be divided into smaller, modular units to address yield limitations. While this approach has enabled picojoule-level (pJ-level) energy consumption for achieving exceptional terabits per second (Tb/s) data throughput within chiplets, this approach faces significant efficiency challenges when it comes to inter-chiplet connections. These challenges arise due to the scaling of interconnections and limitations in pin count and signal integrity, which hinder the overall performance of the system.

[0004] Optical interconnects offer a promising solution to the bottleneck in inter-chiplet communication by providing low-latency, low-loss data transmission. However, the current state-of-the-art optical solutions are limited by the relatively large area required for optical devices and the heat sensitivity associated with lasers. High-speed modulators, despite their advantages, also consume substantial energy. Additionally, the use of fixed interconnects after fabrication restricts system flexibility and can lead to resource inefficiencies, further reducing the effectiveness of the overall system.

[0005] As such, those skilled in the art are continually seeking solutions to optimize interconnectivity between the chiplets by adopting innovative means that improve the system's power efficiency, increase the speed of data transmission between the chiplets and introduce the for reconfigurable optical interconnects.

SUMMARY

[0006] In one aspect, the present disclosure describes an optoelectronic device comprising a photonic interposer having a conductive layer formed on a base substrate and an oxide or dielectric layer formed on the conductive layer such that the conductive layer is interposed between the oxide layer and the base substrate. The oxide layer of the photonic interposer further comprises first and second chiplets that are attached to the surface of the oxide layer. A first micro-ring resonator (MRR) router is disposed on the surface of the oxide layer adjacent to the first chiplet, and the first MRR router is communicatively connected to the first chiplet through a first conductive interconnect layer formed within the oxide layer. A second MRR router is disposed on the surface of the oxide layer adjacent to the second chiplet, and the second MRR router is communicatively connected to the second chiplet through a second conductive interconnect layer formed within the oxide layer. The photonic interposer also has a multimode waveguide that has a first end for receiving optical signals and a second end for transmitting optical signals being formed on the surface of the oxide layer. The waveguide is formed adjacent to the first and the second MRR routers such that the multimode waveguide is electromagnetically coupled to the first and the second MRR routers. Each of the first and second MRR routers further comprises a micro-ring modulator and a memory module.

[0007] In a further embodiment of this aspect, a multi-wavelength multiplexer is formed on the surface of the oxide layer for receiving and combining multi-wavelength optical signals from a laser bank, the multi-wavelength multiplexer being optically coupled to the first end of the multimode waveguide.

[0008] In yet a further embodiment of this aspect, the present disclosure describes a micro-ring modulator of the first MRR router that is configured to resonate at a first wavelength. While the micro-ring modulator is resonating at the first wavelength, it selectively couples an optical signal having the first wavelength from the combined multi-wavelength optical signals that are propagating in the multimode waveguide. It then modulates the coupled optical signal based on data contained in a memory module of the first MRR router and once done, proceeds to couple the modulated optical signal back to the multimode waveguide such that the coupled modulated optical signal then continues to propagate through the multimode waveguide. A micro-ring modulator of the second MRR router is then configured to resonate at the first wavelength. While the micro-ring modulator of the second MRR router is resonating at the first wavelength, it selectively couples the modulated optical signal having the first wavelength from the optical signals propagating in the multimode waveguide. The modulated optical signal is then optically coupled to a high-speed photodetector formed on the surface of the oxide layer adjacent to the second chiplet and the second MRR router. In embodiments of the disclosure, the high-speed photodetector then converts optical signals received by the second MRR router into electrical signals and provides the converted electrical signals to the second chiplet.

[0009] In another aspect, the present disclosure describes a method for forming an optoelectronic device. A photonic interposer is initially formed by the steps of forming a conductive layer on a base substrate and forming an oxide or dielectric layer on the conductive layer such that the conductive layer is interposed between the oxide layer and the base substrate. The method then comprises the steps of attaching a first chiplet to a surface of the oxide layer of the photonic interposer, forming a first micro-ring resonator (MRR) router on the surface of the oxide layer adjacent to the first chiplet, the first MRR router being communicatively connected to the first chiplet through a first conductive interconnect layer formed within the oxide layer, attaching a second chiplet to the surface of the photonic interposer, forming a second MRR router on the surface of the oxide layer adjacent to the second chiplet, the second MRR router being communicatively connected to the second chiplet through a second conductive interconnect layer formed within the oxide layer, and forming a multimode waveguide, having a first end for receiving optical signals and a second end for transmitting optical signals, on the surface of the oxide layer adjacent to the first and the second MRR routers such that the multimode waveguide is electromagnetically coupled to the first and the second MRR routers, wherein the first and second MRR routers each comprise a micro-ring modulator and a memory module.

[0010] In another embodiment of this aspect, the present disclosure describes a method for forming a high-speed photodetector on the surface of the oxide layer adjacent to the second chiplet and the second MRR router, converting, using the high-speed photodetector, optical signals received by the second MRR router into electrical signals, and providing, using the high-speed photodetector, the converted electrical signals to the second chiplet. In embodiments of this aspect, the high-speed photodetector comprises a drop waveguide and a photodiode, wherein the drop waveguide was formed on the surface of the oxide layer adjacent the second MRR router such that the drop waveguide is electromagnetically coupled with a micro-ring modulator of the second MRR router, and the photodiode was attached to the surface of the oxide layer and optically connected to the drop waveguide and communicatively connected to the second chiplet.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Various embodiments of the present disclosure are described below with reference to the following drawings:

[0012] FIG. **1** illustrates a perspective view of an optoelectronic device having a photonic interposer, a plurality of chiplets that are each provided a micro-ring resonator (MRR) router and a multimode waveguide in accordance with an embodiment of the present disclosure;

[0013] FIG. **2** illustrates a cross-sectional view of the optoelectronic device illustrated in FIG. **1** in accordance with an embodiment of the present disclosure;

[0014] FIG. **3** illustrates a top view of an optoelectronic device having a photonic interposer and a plurality of optically interconnected chiplets in accordance with an embodiment of the present disclosure;

[0015] FIG. **4** illustrates a flowchart of a process to form an optoelectronic device in accordance with an embodiment of the present disclosure;

[0016] FIG. **5** illustrates an operational flow of a MRR router in an optoelectronic device in accordance with an embodiment of the present disclosure;

[0017] FIG. **6***a* illustrates the benchmarking results when the optoelectronic device is benchmarked against model reference architectures that utilize 10 nm CMOS technology for various algorithms;

[0018] FIG. **6***b* illustrates the benchmarking results when the optoelectronic device is benchmarked against model reference architectures that utilize 10 nm CMOS technology for various topologies; and

[0019] FIG. **6***c* illustrates the benchmarking results when the optoelectronic device is benchmarked against model reference architectures that utilize 10 nm CMOS technology for various chiplet numbers.

DETAILED DESCRIPTION

[0020] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0021] In the context of various embodiments, the articles "a", "an" and "the" as used with regard to a feature or element include a reference to one or more of the features or elements.

[0022] In the context of various embodiments, the term "about" or "approximately" as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0023] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0024] As used herein, "comprising" means including, but not limited to, whatever follows the word "comprising". Thus, use of the term "comprising" indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0025] As used herein, "consisting of" means including, and limited to, whatever follows the phrase "consisting of". Thus, use of the phrase "consisting of" indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0026] In the context of various embodiments, the term "surround" means to enclose something completely to form a barrier around it. Thus, the use of the term "surround" indicates that something is on all sides of another thing.

[0027] In the context of various embodiments, the term "disposed on" relates to the placement or deposition of one material or layer onto the surface of another and may involve one or more types of deposition techniques.

[0028] In the context of various embodiments, the term "around" or "adjacent" means to be in the proximity or location of something and does not necessarily mean that two objects have to be in contact.

[0029] In the context of various embodiments, the directional terms mentioned herein, such as "above" and "below" or "upper" and "lower" refer to directions as described with reference to the drawings. Therefore, the directional terms are only used for illustration and are not meant to limit the present disclosure.

[0030] It should be noted that although the terms first, second and third are used herein to describe various elements, these elements should not be limited by these terms as these terms are meant to only distinguish one element from another element. Thus, the first element described herein could be termed as a second element without departing from this disclosure.

[0031] As used herein, a "layer" refers to a material portion including a region having a particular thickness. The layer may extend over the entirety of the structure or may cover only part of the structure as defined in the description. For example, a layer may be located between two horizontal planes; may be located between, or at, a top surface and a bottom surface of the structure. The layer may also extend horizontally, vertically, and/or along the surface of the structure.

[0032] As used herein, the term “electromagnetically coupled” in the context of two or more waveguides refers to the interaction of optical signals traveling in these two or more waveguides through electromagnetic fields rather than direct physical or electrical contact. Such a coupling occurs when the electromagnetic field generated by optical signals in one waveguide induces a corresponding response in another nearby waveguide.

[0033] Additionally, for the sake of brevity, extensive explanations of conventional techniques of fabricating semiconductor devices and integrated circuits are not described in detail herein. The tasks and processes described herein may also be integrated into a more comprehensive procedure with extra steps of features that are not elaborated upon in this document. Specifically, certain processes of fabricating semiconductor devices are well known to one skilled in the art hence, such processes will be omitted entirely.

[0034] Photonic interposers are one-piece devices comprising photonic circuits formed of passive and active optical components. Microelectronic chips comprising integrated circuits and/or electronic components may also be physically attached to, and electrically connected to the photonic interposer. The active optical components provided on the photonic interposer may include electro-optical and/or thermo-optical components that act as the electronic interface between the photonic circuits and the microelectronic chips.

[0035] A perspective view of an optoelectronic device in accordance with embodiments of the present disclosure is illustrated in FIG. **1**. As illustrated, optoelectronic device **100** comprises chiplets **108***a* and **108***b*, that are joined or attached to photonic interposer **102** through the use of metal contacts **110** and multi-ring resonators (MRRs) **106***a* and **106***b* that are formed on photonic interposer **102** adjacent to chiplets **108***a* and **108***b* respectively. In embodiments of the disclosure, micro-ring resonators **106***a* and **106***b* each comprise a compact and circular optical waveguide that may be used to selectively filter or route light at specific wavelengths when the MRR resonates at those wavelengths. In embodiments of the disclosure, chiplet **108***b* and corresponding MRR **106***b* are located “downstream” (i.e., along the path a signal takes after leaving a chiplet) of chiplet **108***a* and corresponding MRR **106***a* such that chiplet **108***b* receives data transmitted by chiplet **108***a* as the optical signals propagate along waveguide **104**.

[0036] Optoelectronic device **100** also comprises multimode waveguide **104** that is formed on photonic interposer **102**, adjacent to MRRs **106***a* and **106***b* such that MRRs **106***a* and **106***b* electromagnetically couples optical signals that may be propagating in multimode waveguide **104**, i.e., multimode waveguide **104** is electromagnetically coupled to MRRs **106***a* and **106***b*. In embodiments of the disclosure, optoelectronic device may also be provided with an optical source **112** which may comprise a diode laser, solid-state lasers and any other light source. In the arrangement illustrated in FIG. **1**, multimode waveguide **104** is configured to receive optical signals from optical source **112** at one end, and to transmit optical signals that have propagated through waveguide **104** at another end.

[0037] Chiplets **108***a* and **108***b* comprise combinations of memory component **115**, input/output interface **116**, graphics processing unit (GPU) **117** and/or processing unit **118**. Herein, the term “processing unit” is used to refer generically to any device or component that can process instructions and may include: a core, a microprocessor, a processor, a plurality of processing elements, a microcontroller, a programmable logic device or any other type of computational device. That is, processing unit **118** may be provided by any suitable logic circuitry for receiving inputs, processing them in accordance with instructions stored in memory component **115** and generating outputs (for example to the memory components or to the multi-ring resonator routers). In this embodiment, processing unit **118** may be a single core or multi-core processor with memory addressable space. In one example, processing unit **118** may be multi-core, comprising—for example—an 8 core CPU, or it could be a cluster of CPU cores operating in parallel to accelerate computations. In embodiments of the disclosure, GPU **117** may comprise a specialized processor designed to handle parallel processing tasks, making it ideal not only for graphics-related computations but also for general-purpose computing tasks like machine learning and scientific simulations. One skilled in the art will recognize that chiplet **108** may comprise of other electronic components and/or memory components and the components illustrated in FIG. **1** are shown as a non-limiting exemplary configuration of such a chiplet.

[0038] Memory component **115** include both volatile and non-volatile memory and may include more than one of each type of memory, including Random Access Memory (RAM), Read Only Memory (ROM) or a mass storage device, the last comprising one or more solid-state drives (SSDs). One skilled in the art will recognize that the memory components described above comprise non-transitory computer-readable media and shall be taken to comprise all computer-readable media except for a transitory, propagating signal. Typically, the instructions are stored as program code in the memory components but can also be hardwired. Memory component **115** may include a kernel and/or programming modules such as a software application that may be stored in either volatile or non-volatile memory.

[0039] It should be noted that an orthogonal three-dimensional coordinate system x-y-z is defined in FIGS. **1** and **2**, in which the x- and z-axes form a plane parallel to the main plane of photonic interposer **102**, and in which the +y axis is oriented in a perpendicular direction to a surface of photonic interposer **102**.

[0040] A cross-sectional view of optoelectronic device **100** along the y-z plane is illustrated in FIG. **2**. As shown, photonic interposer **102** is formed from a stack of layers comprising conductive layer **204** that is sandwiched between base substrate **202** and dielectric layer **206**. In embodiments of the disclosure, conductive layer **204** is formed on base substrate **202**, whereby base substrate **202** may comprise, but is not limited to, silicon, silicon dioxide, silicon nitride, etc., while conductive layer **204** may comprise any conductive material such as gold, platinum, aluminum, etc. or solder/conductive balls comprising a conductive material. Dielectric layer **206** is then formed on conductive layer **204** such that conductive layer **204** is interposed or sandwiched between dielectric layer **206** and base substrate **202**. In embodiments of the disclosure, dielectric layer **206** may comprise of any insulating materials such as silicon dioxide, silicon nitride, etc.

[0041] As illustrated in FIG. **2**, chiplet **108***a* is attached to a surface of dielectric layer **206**. Micro-ring resonator (MRR) **106***a* and multimode waveguide **104** are also disposed on the surface of dielectric layer **206** such that MRR **106***a* is electromagnetically coupled to multimode waveguide **104**. Electronic components **212**, which are provided on chiplet **108***a*, are communicatively connected to MRR **106***a* through conductive interconnects **208** and/or **210**, which are formed within dielectric layer **206**. In embodiments of the disclosure, each processing unit of chiplet **108***a* may be connected to MRR **106***a* via its own conductive interconnect formed within dielectric layer **206** or the processing units may share a single conductive interconnect formed within dielectric layer **206**. In embodiments of the disclosure, electronic components may comprise, but is not limited to, combinations of memory component **115**, input/output interface **116**, GPU **117** and/or processing unit **118**.

[0042] FIG. **3** illustrates a top view of dynamic photonic interconnect system **300** comprising a plurality of chiplets **310-318** that are attached to a surface of photonic interposer **102**, and multimode waveguide **104** and multi-wavelength multiplexer **304** that are formed on the surface of photonic interposer **102**, whereby multi-wavelength multiplexer **304** is optically coupled to an end of multimode-waveguide **104**. Each of chiplets **310-318** comprises a micro-ring resonator (MRR) router, wherein each MRR router comprises micro-ring modulator **306**, which performs as a channel selector and high-speed encoder/decoder, and memory module **308**. Although FIG. **3** illustrates that system **100** comprises chiplets **310-318**, one skilled in the art will recognize that system **100** may comprise any number of chiplets and that the number of chiplets attached to photonic interposer **102** is just for illustrative purposes only.

[0043] In operation, multi-wavelength optical signals **302**, that may be generated by a laser bank, are first provided to multiplexer **304**. In embodiments of the disclosure, the laser bank may be integrated into system **300** and may house individual lasers that generate optical signals of different wavelengths. Upon receiving the multi-wavelength optical signals, multiplexer **304** combines these signals and optically couples the combined optical signals to multimode waveguide **104**. The combined multi-wavelength optical signals then propagate through multimode waveguide **104** until it is transmitted at end **305** of waveguide **104**. As the combined multi-wavelength optical signals propagate through multimode waveguide **104**, system **300** is able to achieve multi-channel capability as optical signals with specific wavelengths may be selectively coupled and encoded, and/or coupled and decoded according to the resonant frequency of each micro-ring modulator **306**.

[0044] In an embodiment of the disclosure, a router controller (not shown) may be communicatively connected to chiplets **310-318** and may be used to identify available optical channels (i.e., free wavelengths) in multimode waveguide **104** for communication between any of chiplets **310-318**. For example, if the router controller determines that chiplet **318** intends to communicate with chiplet **312**, the router controller will first identify and select an optical signal having a specific wavelength from the combined multi-wavelength optical signals propagating through multimode waveguide **104** to establish a photonic communication channel between chiplets **318** and **312**. For instance, the router controller may choose to use an optical signal at a first wavelength λ_1 from the propagating combined multi-wavelength optical signals. At the same time, the router controller may cause the time-series data to be communicated to chiplet **318** to be stored into memory module **318***c* associated with chiplet **318**.

[0045] As the optical signal having the first wavelength λ_1 is selected by the router controller, micro-ring modulator **318***c* associated with chiplet **318** will then be triggered to resonate at the first wavelength λ_1. When the combined optical signals pass by micro-ring modulator **318***c*, the optical signal having the first wavelength λ_1 will be selectively electromagnetically coupled into micro-ring modulator **318***c*.

[0046] Once the optical signal at the first wavelength λ_1 has been electromagnetically coupled into micro-ring modulator **318***c*, the coupled signal begins to resonate within micro-ring modulator **318***c*, causing the optical signal to circulate within the ring structure. While the optical signal is resonating in micro-ring modulator **318***c*, the time-series data stored in memory module **318***b* is used by chiplet **318** to modulate the optical signal circulating within micro-ring modulator **318***c*. In embodiments of the disclosure, the modulation of the optical signal may be achieved by altering the refractive index of the material in micro-ring modulator **318***c*. This change in refractive index may be controlled by applying an electric field, which may be directly correlated with the data retrieved from the memory module, i.e. through the electro-optic effect. In embodiments of the disclosure, the change in the refractive index may additionally be controlled by applying heat to the material in micro-ring modulator **318***c*, i.e., through the thermo-optic effect.

[0047] The modulation process encodes the time-series data onto the optical signal by varying the phase, amplitude, or frequency of the light as it resonates in micro-ring modulator **318***c*. For example, the electric field applied to micro-ring modulator **318***c* may shift the resonant wavelength slightly, where this shift can be used to represent different bits of data (e.g., a phase shift could represent a binary '1' or '0'). In another example, the amplitude of the resonating light might be modulated to encode the data. Regardless of the modulation technique used, the result is the creation of an optical signal that carries the encoded information as it circulates within micro-ring modulator **318***c*.

[0048] Once the optical signal is fully modulated with the data contained in memory module **318***b*, the modulated optical signal exits micro-ring modulator **318***c* and re-couples into the multimode waveguide **104** through electromagnetic coupling. This occurs as the optical signal in micro-ring modulator **318***c* continuously interacts with the evanescent field of multimode waveguide **104**. As a result, when the resonance condition within micro-ring modulator **318***c* is altered (through modulation or natural decay), the optical signal begins to transfer back into waveguide **104**. The modulated optical signal, now carrying the encoded data, propagates through multimode waveguide **104** towards its destination, chiplet **312**.

[0049] As chiplet **312** is meant to receive the encoded data, micro-ring modulator **312***c* associated with chiplet **312** is triggered to resonate at the first wavelength λ_1. When the combined optical signals pass by micro-ring modulator

312_c_, the modulated optical signal at the first wavelength λ_1 is selectively electromagnetically coupled into micro-ring modulator **312**_c_. The modulated optical signal circulating in micro-ring modulator **312**_c_ is then coupled to a high-speed photodetector (not shown) formed on the surface of photonic interposer **102**, adjacent to micro-ring modulator **312**_c_.

[0050] In embodiments of the disclosure, the high-speed photodetector comprises a drop waveguide and a photodiode (both not shown). The drop waveguide is formed on the surface of photonic interposer **102** adjacent micro-ring modulator **312**_c_ such that the drop waveguide is electromagnetically coupled with micro-ring modulator **312**_c_. The photodiode, attached to the surface of the dielectric layer, is optically connected to the drop waveguide and communicatively connected to chiplet **312**. When the drop waveguide receives the modulated optical signal from micro-ring modulator **312**_c_, the drop waveguide then provides the modulated optical signal to the photodiode, which proceeds to convert the optical signals into electrical signals. The electrical signals containing the encoded data are then provided to chiplet **312** where it is decoded and processed further. The electrical signals may also be simultaneously stored in memory module **312**_b_ for further processing. In embodiments of the disclosure, the high-speed photodetector may be provided adjacent to any micro-ring modulator shown in FIG. **3** where optical signals are to be converted into electrical signals for further processing by an associated chiplet.

[0051] In further embodiments of the disclosure, to ensure that the modulated optical signal from chiplet **318** is received by chiplet **312**, the router controller will cause the micro-ring modulators of all remaining chiplets, i.e., chiplets **310**, **311**, **313**, **314**, **315**, **316**, **317**—to resonate at wavelengths other than the first wavelength λ_1. This ensures that the modulated optical signal at the first wavelength λ_1 will not be intercepted by other chiplets other than the one for which the signal is intended for.

[0052] In further embodiments of the disclosure, while data is being exchanged between chiplets **318** and **312**, communication may also take place concurrently between chiplets **316** and **314**, as long as the communication occurs using an optical signal at a different wavelength, i.e. a second wavelength λ_2.

[0053] To initiate communication between chiplets **316** and **314**, the router controller identifies and selects an optical signal at the second wavelength λ_2 from the combined multi-wavelength optical signals propagating through multimode waveguide **104**. Micro-ring modulator **316**_c_ associated with chiplet **316** is then triggered to resonate at the second wavelength λ_2. As the combined optical signals pass by micro-ring modulator **316**_c_, including the previously modulated optical signal at the first wavelength λ_1, only the optical signal at the second wavelength λ_2 is selectively electromagnetically coupled into micro-ring modulator **316**_c_.

[0054] Once the optical signal at the second wavelength λ_2 is coupled into micro-ring modulator **316**_c_, it is then modulated using the time-series data obtained from memory module **316**_b_ through changes in the refractive index of micro-ring modulator **316**_c_, similar to the process described previously for chiplet **318**.

[0055] After modulation, the optical signal at the second wavelength λ_2 exits micro-ring modulator **316**_c_ and re-couples into multimode waveguide **104**. The combined optical signals in multimode waveguide **104** now carries the optical signals with encoded data at the first and second wavelengths λ_1 and λ_2 and propagates through the multimode waveguide towards their respective destinations. To ensure that the modulated optical signal at the second wavelength λ_2 reaches chiplet **314** without interference, the router controller ensures that the micro-ring modulators of other chiplets are either not resonating at the second wavelength λ_2 or are tuned to different wavelengths.

[0056] When the modulated optical signal at the second wavelength λ_2 approaches chiplet **314**, the modulated optical signal is then selectively electromagnetically coupled into micro-ring modulator **314**_c_, which has been triggered to resonate at the second wavelength λ_2. The modulated optical signal in micro-ring modulator **314**_c_ is subsequently coupled to a high-speed photodetector formed on the surface of photonic interposer **102** and is processed as previously described where the converted electrical signals may be provided to chiplet **314** or stored in memory module **314**_b_.

[0057] In further embodiments of the disclosure, memory controller **320** may be provided on the surface of photonic interposer **102** and may be communicatively connected to all the memory modules provided in system **300**. The function of memory controller **320** is to manage the interaction between each of the memory modules thereby ensuring that the modulation and/or processing by the respective chiplets are correctly stored and retrieved when required. Memory controller **320** also coordinates the timing and synchronization of data exchange between the memory modules and other components of system **300**.

[0058] A process for fabricating or forming an optoelectronic device in accordance with an embodiment of this disclosure is illustrated in FIG. **4**. Process **400** may be performed using standard semiconductor fabrication or manufacturing steps. Process **400** begins at step **402**. At this step, a photonic interposer comprising a conductive layer interposed between a dielectric layer and a base substrate is initially formed. Specifically, process **400** first forms the conductive layer on the base substrate. The dielectric layer is then formed on the conductive layer.

[0059] At step **404**, process **400** then attaches a first chiplet to a surface of the dielectric layer of the photonic interposer. Process **400** then forms a first micro-ring resonator (MRR) router on the surface of the dielectric layer adjacent to the first chiplet, where the first MRR router is communicatively connected to the first chiplet through a first conductive interconnect layer formed within the dielectric layer. This takes place at step **406**. At step **408**, process **400** then attaches a second chiplet to the photonic interposer. Process **400** then forms a second MRR router on the surface of the dielectric layer adjacent to the second chiplet, where the second MRR router is communicatively connected to the second chiplet through a second conductive interconnect layer formed within the dielectric layer and this occurs at step **410**. Process **400** then proceeds to step **412** where process **400** forms a multimode waveguide on the surface of the dielectric layer adjacent to the first and the second MRR routers such that the multimode waveguide is electromagnetically coupled to the first and the second MRR routers. The multimode waveguide has a first end for receiving optical signals and a second end for transmitting optical signals.

[0060] In further embodiments of the disclosure, process **400** forms a high-speed photodetector on the surface of the dielectric layer adjacent to the second chiplet and the second MRR router, converts, using the high-speed photodetector, optical signals received by the second MRR router into electrical signals, and provides, using the high-speed photodetector, the converted electrical signals to the second chiplet.

[0061] In further embodiments of the disclosure, the high-speed photodetector comprises a drop waveguide and a photodiode. The drop waveguide is formed on the surface of the dielectric layer adjacent the second MRR router such that the drop waveguide is electromagnetically coupled with a micro-ring modulator of the second MRR router, and the photodiode is attached to the surface of the dielectric layer and optically connected to the drop waveguide while being communicatively connected to the second chiplet.

[0062] In further embodiments of the disclosure, process **400** forms a multi-wavelength multiplexer on the surface of the dielectric layer for receiving and combining multi-wavelength optical signals from a laser bank, and optically couples the multi-wavelength multiplexer to the first end of the multimode waveguide.

[0063] In further embodiments of the disclosure, process **400** resonates a micro-ring modulator of the first MRR router at a first wavelength, selectively couples, using the resonating micro-ring modulator of the first MRR router, an optical signal having the first wavelength from the combined multi-wavelength optical signals propagating in the multimode waveguide, modulates, using the resonating micro-ring modulator of the first MRR router, the coupled optical signal based on data contained in a memory module of the first MRR router, and couples, using the resonating micro-ring modulator of the first MRR router, the modulated optical signal to the multimode waveguide such that the coupled modulated optical signal propagates through the multimode waveguide.

[0064] In further embodiments of the disclosure, process **400** resonates a micro-ring modulator of the second MRR router at the first wavelength, selectively couples, using the resonating micro-ring modulator of the second MRR router, the modulated optical signal having the first wavelength from the optical signals propagating in the multimode waveguide, and optically couples, using the resonating micro-ring modulator of the second MRR router, the modulated optical signal to a high-speed photodetector formed on the surface of the dielectric layer adjacent to the second chiplet and the second MRR router.

[0065] In further embodiments of the disclosure, process **400** causes the first MRR router to modulate the coupled optical signal using electro-optic modulation or thermo-optic modulation. Process **400** also forms the base substrate from a thick silicon layer and the dielectric layer from a silicon dioxide layer.

[0066] In further embodiments of the disclosure, process **400** attaches a third chiplet to the surface of the dielectric layer of the photonic interposer. Process **400** then forms a third MRR router on the surface of the dielectric layer adjacent to the third chiplet and adjacent to the multimode waveguide such that the multimode waveguide is electromagnetically coupled to the third MRR router, the third MRR router being communicatively connected to the third chiplet through a third conductive interconnect layer formed within the dielectric layer, whereby the third MRR router is interposed in an optical signal path between the first and second MRR routers. Process **400** then resonates a micro-ring modulator of the third MRR router at a second wavelength and selectively couples, using the resonating micro-ring modulator of the third MRR router, an optical signal having the second wavelength from the combined multi-wavelength optical signals propagating in the multimode waveguide, whereby the modulated optical signal having the first wavelength continues to propagate through the multimode waveguide. Process **400** then modulates, using the resonating micro-ring modulator of the third MRR router, the coupled optical signal having the second wavelength based on data contained in a memory module of the third MRR router, and couples, using the resonating micro-ring modulator of the third MRR router, the modulated optical signal having the second wavelength to the multimode waveguide such that the coupled modulated optical signal having the second wavelength propagates through the multimode waveguide.

[0067] An operational flow of a MRR router in an opto-electronic device in accordance with an embodiment of the present disclosure is illustrated in FIG. **5**. In this illustration, the combined optical signals propagating through the multimode waveguide comprises four optical signals at four different wavelengths, i.e., WL_0, WL_1, WL_2, WL_3.

[0068] Stage **502** represents the step where no action has been taken by a chiplet associated with the MRR router. Hence, it can be seen from light transmission signals **501** that the MRR router is not resonating at any of the four different wavelengths WL_0, WL_1, WL_2, WL_3.

[0069] Stage **504** represents the step where the optical signal at wavelength WL_2 is selected as the optical signal that is to be used as the photonic communication channel between chiplets of the optoelectronic device. At this stage, an appropriate biasing voltage, V_{MEM} is applied to the MRR router to cause the micro-ring modulator of the MRR router to resonate at the wavelength WL_2. As a result, light transmission signals **501** as illustrated in the plot at stage **504** are now shown to resonate at the wavelength WL_2 as well.

[0070] Stage **506** represents the step where the circulating optical signal at wavelength WL_2 is encoded with a bit of data representing a binary '0'. In this illustration, the encoding of the data is carried out by performing phase-shifts on the circulating optical signal. Hence, as a binary '0' is to be encoded, the wavelength of the circulating optical signal is not "phase-shifted".

[0071] Stage **508** represents the step where the circulating optical signal at wavelength WL_2 is encoded with a bit of data representing a binary '1', and this is achieved by performing a phase-shift on the circulating optical signal. Hence, as shown in the plot at stage **508**, it can be seen that light transmission signals **501** has been slightly phase-shifted to a higher wavelength.

[0072] The steps performed at stages **506** and **508** may then be repeated and/or altered as required until all the data has been encoded onto the optical signal. The encoded optical signal is then coupled back into the waveguide and communicated to the destination chiplet where it is decoded and processed accordingly. In embodiments of the disclosure, up to five (5) bits of data may be simultaneously encoded onto the optical signal.

Simulation Results

[0073] An optoelectronic device as described above is modeled using a 10 nm complementary metal-oxide-semiconductor (CMOS) technology. Benchmark tests are then performed on the simulated model based on different interconnect topologies such as electrical router/electrical interconnect (E/E), electrical router/optical interconnect (E/O) and optical router/optical interconnect (O/O), for various algorithms (see FIG. **6***a*), mesh topologies (see FIG. **6***b*) and chiplet numbers (see FIG. **6***c*). The algorithms plotted in FIG. **6***a* comprise betweenness centrality (BC), breadth-first search (BFS), breadth-first search connected components (BFSCC), clustering coefficient (CF), K-Core decomposition (Kcore), maximal independent set (MIS), Radii, components (CPs), page rank (PR) and triangle (TG) algorithms. The detailed workings of these algorithms are omitted for brevity as they are well known in the art.

[0074] Numerous other changes, substitutions, variations, and modifications may be ascertained by the skilled in the art and it is intended that the present application encompass all such changes, substitutions, variations and modifications as falling within the scope of the appended claims.

1. An optoelectronic device comprising:
- a photonic interposer comprising:
  - a conductive layer formed on a base substrate;
  - a dielectric layer formed on the conductive layer such that the conductive layer is interposed between the dielectric layer and the base substrate;
- a first chiplet attached to a surface of the dielectric layer of the photonic interposer;
- a first micro-ring resonator (MRR) router disposed on the surface of the dielectric layer adjacent to the first chiplet, the first MRR router being communicatively connected to the first chiplet through a first conductive interconnect layer formed within the dielectric layer;
- a second chiplet attached to the surface of the photonic interposer;
- a second MRR router disposed on the surface of the dielectric layer adjacent to the second chiplet, the second MRR router being communicatively connected to the second chiplet through a second conductive interconnect layer formed within the dielectric layer;
- a multimode waveguide having a first end for receiving optical signals and a second end for transmitting optical signals, the multimode waveguide being formed on the surface of the dielectric layer and positioned adjacent to the first and the second MRR routers such that the first and the second MRR routers electromagnetically couples with the optical signals within the multimode waveguide,
- wherein the first and second MRR routers each comprise a micro-ring modulator and a memory module.

2. The optoelectronic device according to claim **1**, further comprising:
- a high-speed photodetector formed on the surface of the dielectric layer adjacent to the second chiplet and the second MRR router, the high-speed photodetector being configured to convert optical signals received by the second MRR router into electrical signals and to provide the converted electrical signals to the second chiplet.

3. The optoelectronic device according to claim **2**, wherein the high-speed photodetector comprises a drop waveguide and a photodiode, wherein the drop waveguide is formed on the surface of the dielectric layer adjacent the second MRR router such that the drop waveguide electromagnetically couples with optical signals within a micro-ring modulator of the second MRR router, and the photodiode is attached to the surface of the dielectric layer and optically connected to the drop waveguide and communicatively connected to the second chiplet.

4. The optoelectronic device according to claim **1**, further comprising:
- a multi-wavelength multiplexer formed on the surface of the dielectric layer for receiving and combining multi-wavelength optical signals from a laser bank, the multi-wavelength multiplexer being optically coupled to the first end of the multimode waveguide.

5. The optoelectronic device according to claim **4**, whereby a micro-ring modulator of the first MRR router is configured to:
- resonate at a first wavelength;
- selectively couple an optical signal having the first wavelength from the combined multi-wavelength optical signals propagating in the multimode waveguide;
- modulate the coupled optical signal based on data contained in a memory module of the first MRR router; and
- couple the modulated optical signal to the multimode waveguide such that the coupled modulated optical signal propagates through the multimode waveguide.

6. The optoelectronic device according to claim **5**, whereby a micro-ring modulator of the second MRR router is configured to:
- resonate at the first wavelength;
- selectively couple the modulated optical signal having the first wavelength from the optical signals propagating in the multimode waveguide; and
- coupling the modulated optical signal to a high-speed photodetector formed on the surface of the dielectric layer adjacent to the second chiplet and the second MRR router.

7. The optoelectronic device according to claim **5**, wherein the first MRR router modulates the coupled optical signal using electro-optic modulation or thermo-optic modulation.

8. The optoelectronic device according to claim **1**, wherein the base substrate comprises a thick silicon layer.

9. The optoelectronic device according to claim **1**, wherein the dielectric layer comprises a silicon dioxide layer.

10. The optoelectronic device according to claim **1**, further comprising:
- a third chiplet attached to the surface of the dielectric layer of the photonic interposer;
- a third MRR router disposed on the surface of the dielectric layer adjacent to the third chiplet and adjacent to the multimode waveguide such that the third MRR router electromagnetically couples with the optical signals within the multimode waveguide, the third MRR router being communicatively connected to the third chiplet through a third conductive interconnect layer formed within the dielectric layer, whereby the third MRR router is interposed in an optical signal path between the first and second MRR routers;
- a micro-ring modulator of the third MRR router being configured to:
  - resonate at a second wavelength;
  - selectively couple an optical signal having the second wavelength from the combined multi-wavelength optical signals propagating in the multimode waveguide, whereby the modulated optical signal having

the first wavelength continues to propagate through the multimode waveguide;

modulate the coupled optical signal having the second wavelength based on data contained in a memory module of the third MRR router; and

couple the modulated optical signal having the second wavelength to the multimode waveguide such that the coupled modulated optical signal having the second wavelength propagates through the multimode waveguide.

11. A method for forming an optoelectronic device, the method comprising:

forming a photonic interposer comprising the steps of:

forming a conductive layer on a base substrate;

forming a dielectric layer on the conductive layer such that the conductive layer is interposed between the dielectric layer and the base substrate;

attaching a first chiplet to a surface of the dielectric layer of the photonic interposer;

forming a first micro-ring resonator (MRR) router on the surface of the dielectric layer adjacent to the first chiplet, the first MRR router being communicatively connected to the first chiplet through a first conductive interconnect layer formed within the dielectric layer;

attaching a second chiplet to the surface of the photonic interposer;

forming a second MRR router on the surface of the dielectric layer adjacent to the second chiplet, the second MRR router being communicatively connected to the second chiplet through a second conductive interconnect layer formed within the dielectric layer;

forming a multimode waveguide, having a first end for receiving optical signals and a second end for transmitting optical signals, on the surface of the dielectric layer adjacent to the first and the second MRR routers such that the first and the second MRR routers electromagnetically couples with the optical signals within the multimode waveguide,

wherein the first and second MRR routers each comprise a micro-ring modulator and a memory module.

12. The method according to claim **11**, further comprising the step of:

forming a high-speed photodetector on the surface of the dielectric layer adjacent to the second chiplet and the second MRR router;

converting, using the high-speed photodetector, optical signals received by the second MRR router into electrical signals; and

providing, using the high-speed photodetector, the converted electrical signals to the second chiplet.

13. The method according to claim **12**, wherein the high-speed photodetector comprises a drop waveguide and a photodiode, wherein the drop waveguide is formed on the surface of the dielectric layer adjacent the second MRR router such that the drop waveguide electromagnetically couples with optical signals within a micro-ring modulator of the second MRR router, and the photodiode is attached to the surface of the dielectric layer and optically connected to the drop waveguide and communicatively connected to the second chiplet.

14. The method according to claim **11**, further comprising:

forming a multi-wavelength multiplexer on the surface of the dielectric layer for receiving and combining multi-wavelength optical signals from a laser bank; and

optically coupling the multi-wavelength multiplexer to the first end of the multimode waveguide.

15. The method according to claim **14**, further comprising the steps of:

resonating a micro-ring modulator of the first MRR router at a first wavelength;

selectively coupling, using the resonating micro-ring modulator of the first MRR router, an optical signal having the first wavelength from the combined multi-wavelength optical signals propagating in the multimode waveguide;

modulating, using the resonating micro-ring modulator of the first MRR router, the coupled optical signal based on data contained in a memory module of the first MRR router; and

coupling, using the resonating micro-ring modulator of the first MRR router, the modulated optical signal to the multimode waveguide such that the coupled modulated optical signal propagates through the multimode waveguide.

16. The method according to claim **15**, further comprising the steps of:

resonating a micro-ring modulator of the second MRR router at the first wavelength;

selectively coupling, using the resonating micro-ring modulator of the second MRR router, the modulated optical signal having the first wavelength from the optical signals propagating in the multimode waveguide; and

optically coupling, using the resonating micro-ring modulator of the second MRR router, the modulated optical signal to a high-speed photodetector formed on the surface of the dielectric layer adjacent to the second chiplet and the second MRR router.

17. The method according to claim **15**, wherein the first MRR router modulates the coupled optical signal using electro-optic modulation or thermo-optic modulation.

18. The method according to claim **11**, wherein the base substrate comprises a thick silicon layer.

19. The method according to claim **11**, wherein the dielectric layer comprises a silicon dioxide layer.

20. The method according to claim **11**, further comprising the steps of:

attaching a third chiplet to the surface of the dielectric layer of the photonic interposer;

forming a third MRR router on the surface of the dielectric layer adjacent to the third chiplet and adjacent to the multimode waveguide such that the third MRR router electromagnetically couples with the optical signals within the multimode waveguide, the third MRR router being communicatively connected to the third chiplet through a third conductive interconnect layer formed within the dielectric layer, whereby the third MRR router is interposed in an optical signal path between the first and second MRR routers;

resonating a micro-ring modulator of the third MRR router at a second wavelength;

selectively coupling, using the resonating micro-ring modulator of the third MRR router, an optical signal having the second wavelength from the combined multi-wavelength optical signals propagating in the multimode waveguide, whereby the modulated optical signal having the first wavelength continues to propagate through the multimode waveguide;

modulating, using the resonating micro-ring modulator of the third MRR router, the coupled optical signal having the second wavelength based on data contained in a memory module of the third MRR router; and

coupling, using the resonating micro-ring modulator of the third MRR router, the modulated optical signal having the second wavelength to the multimode waveguide such that the coupled modulated optical signal having the second wavelength propagates through the multimode waveguide.

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