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(54) **Title:** METHODS, DEVICES, AND ARCHITECTURES FOR INTER-SPACECRAFT OPTICAL COMMUNICATION

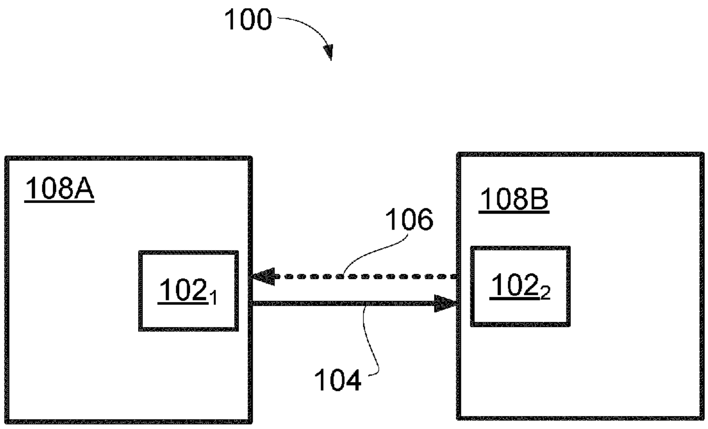

FIG. 1A

(57) **Abstract:** Methods and devices for inter-spacecraft optical communication are described. The device comprises a transmitter for generating a first multi-wavelength signal composed of a first set of wavelengths; a receiver for detecting a second multi-wavelength signal composed of a second set of wavelengths mutually exclusive from the first set of wavelengths; at least one first optical component configured for propagating the first multi-wavelength signal into free space and for capturing the second multi-wavelength signal from free space, the first and second multi-wavelength signals propagating collinearly in free space in opposite directions; and at least one second optical component coupled between the transmitter, the receiver, and the at least one first optical component, and configured for discriminating between the first multi-wavelength signal and the second multi-wavelength signal and redirecting the first multi-wavelength signal to the at least one first optical component and the second multi-wavelength signal to the receiver.

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METHODS, DEVICES, AND ARCHITECTURES FOR INTER-SPACECRAFT OPTICAL COMMUNICATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of United States Provisional Patent Application No. 62/972,804 filed on February 11, 2020, the contents of which are hereby incorporated by reference in their entirety.

TECHNICAL FIELD

[0002] The present disclosure relates generally to free space optical communication and more particularly, to free space optical communication between spacecraft.

BACKGROUND OF THE ART

[0003] Free-space optical communication uses light propagating in free space to wirelessly transmit data for telecommunications or computer networking, without the use of optical fiber cables. The technology is useful where physical connections are impractical, such as in outer space.

[0004] In outer space, inter-satellite optical communication links are established in order to cover long distances. Some of the issues that inter-satellite communication links face are latency and bandwidth. To be practical, the laser terminal architecture and the network architecture must be implemented by size, weight and power constraint hardware.

[0005] Therefore, improvements are needed.

SUMMARY

[0006] In accordance with a broad aspect, there is provided an optical device for inter-spacecraft communication. The device comprises a first transmitter for generating a first multi-wavelength signal composed of a first set of wavelengths; a first receiver for detecting a second multi-wavelength signal composed of a second set of wavelengths mutually exclusive from the first set of wavelengths; at least one first optical component configured for propagating the first multi-wavelength signal into free space and for capturing the second multi-wavelength signal from free space, the first and second multi-wavelength signals propagating collinearly in free space in opposite directions; and at least one second optical component coupled between the first transmitter, the first receiver, and the at least one first optical component, and configured for discriminating between the first multi-wavelength signal and the second multi-wavelength signal and redirecting the first multi-wavelength signal to the at least one first optical component and the second multi-wavelength signal to the first receiver.

[0007] In accordance with another broad aspect, there is provided a method for inter-spacecraft optical communication. The method comprises generating, at a first optical device, a first multi-wavelength signal composed of a first set of wavelengths; propagating the first multi-wavelength signal into free space from the first optical device; capturing from free space, at the first optical device, a second multi-wavelength signal composed of a second set of wavelengths mutually exclusive from the first set of wavelengths, the first and second multi-wavelength signals propagating collinearly in free space in opposite directions along an optical path; detecting the second multi-wavelength signal at the first optical device; and discriminating between the first multi-wavelength signal and the second multi-wavelength signal at the first optical device and redirecting the first multi-wavelength signal for the propagating and the second multi-wavelength signal for the detecting.

[0008] Features of the systems, devices, and methods described herein may be used in various combinations, in accordance with the embodiments described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Reference is now made to the accompanying figures in which:

[0010] Figs. 1A-1D are block diagrams of example networks of spacecraft communicating through optical communication links;

[0011] Fig. 2 is a block diagram of an example optical device for inter-spacecraft optical communication;

[0012] Fig. 3A is a graphical illustration of a first embodiment of mutually exclusive multi-wavelength signals;

[0013] Fig. 3B is a graphical illustration of a second embodiment of mutually exclusive multi-wavelength signals;

[0014] Fig. 4 is a block diagram of an example embodiment for the beam discriminating optics;

[0015] Figs. 5A-5B are example embodiments of transmitters and receivers of the optical device for inter-spacecraft optical communication;

[0016] Fig. 6 is a block diagram of an example spacecraft having a plurality of optical devices sharing a processing device; and

[0017] Figs. 7A-7C are block diagrams of example embodiments of the beam coupling optics.

[0018] It will be noted that throughout the appended drawings, like features are identified by like reference numerals.

DETAILED DESCRIPTION

[0019] Internet-of-things, content streaming and cloud-based solutions are pushing the connectivity demand in developed and developing countries. However, there is a digital divide, i.e. a gap in terms of access to and usage of information and communication technology across the world. It was traditionally considered to be a question of having or not having access, but with a global mobile phone penetration of over 95%, it is becoming a relative inequality between those who have more and those who have less bandwidth. Remote territories or developing countries are part of this digital divide, which can be reduced with satellite-based communication that can offer signals globally.

[0020] Satellite-based internet promises to cover remote territories and territories that do not have access to fibered network and communication towers. In order to compete with fibered networks, the communication system latency must be low. Satellites being deployed on low earth orbit (LEO) and very low earth orbit (VLEO) provides a manageable level of latency. At higher altitudes, satellites can settle into a geostationary orbit, moving at a speed that matches the Earth's rotation and appearing to hover over a fixed spot. In comparison, LEO satellites travel around the planet at around 8 kilometers per second, completing a full circuit in between 90 and 120 minutes. That means they are only visible for a small part of their orbit to receivers on the ground. Thus, multiple satellites are necessary to establish a permanent internet connection, with one satellite passing duties to the next as it approaches the horizon.

[0021] In order to extract the full connectivity potential from constellations of satellites, inter-satellite links must be established. The data can be beamed from one satellite to the other over few thousands' of kilometers. Optical inter-satellite links does higher bandwidth then Ka band RF signals because of the frequency being higher in the infrared range. Moreover, the propagating beam, if diffraction limited, can be kept very confined on long distances. This reduces overlap of connecting signals that form the communication mesh and also reduces the interference. Such optical beams need an average power in the multiple watts range.

[0022] There are described herein optical devices for high power, multiband, bidirectional inter-spacecraft communication. In order to keep each spacecraft as lightweight, small, and low cost as possible, the optical devices are designed with low component count through strategic component sharing. Scalability of bandwidth and/or bitrate is provided by having one optical device capable of geometrically coupling pairs of multi-wavelength signals having mutually exclusive wavelengths.

[0023] Fig. 1A illustrates a network 100 of spacecraft 108A-B having optical communication capabilities. At least one of the spacecraft 108A in the network 100 comprises an optical device 102_1 configured for multi-wavelength bidirectional inter-spacecraft communication, as will be described in more detail below. In some embodiments, the optical device 102_1 is a sub-system of the spacecraft 108A, as illustrated. In some embodiments, the optical device 102_1 forms the entirety of the spacecraft 108A. The spacecraft 108A may be a satellite or any other vehicle, machine or fixed infrastructure designed to fly in outer space or reside on a planet, such as a rover or communication tower on the moon or on mars.

[0024] The optical device 102_1 can propagate a first data communication multi-wavelength signal 104 into free space and capture a second data communication multi-wavelength signal 106 from free space, for example towards and from another spacecraft 108B. Spacecraft 108B comprises optical device 102_2 configured for propagating the second multi-wavelength signal 106 into free space and capturing the first multi-wavelength signal 104 from free space. In some embodiments, one or more components are provided between the two spacecraft 108A, 108B having optical devices 102_1, 102_2, respectively, such as a signal booster, a signal repeater, and the like. It will be understood that the optical device 102_1 may transmit the first multi-wavelength signal 104 to any device capable of receiving signal 104, and may receive the second multi-wavelength signal 106 from any device capable of transmitting said signal 106.

[0025] The first and second multi-wavelength signals 104, 106 propagate in free space collinearly in opposite directions along an optical path. The first multi-wavelength signal 104 is composed of a first set of wavelengths $[\lambda_1, \ldots \lambda_n]$. The second multi-wavelength signal 106 is composed of a second set of wavelengths $[\lambda_a, \ldots \lambda_m]$. The first and second sets of wavelengths are mutually exclusive, i.e. each individual wavelength from the first set of wavelengths $[\lambda_1, \ldots \lambda_n]$ is different from each individual wavelength from the second set of wavelengths $[\lambda_a, \ldots \lambda_m]$. In some embodiments, $n = m$ such that the number of wavelengths in each signal 104, 106 is the same. Alternatively, more or less wavelengths may be provided in either one of signals 104, 106.

[0026] In some embodiments, pairs of counter-propagating, collinear, mutually exclusive multi-wavelength signals may be propagated and captured along two or more optical paths from a same spacecraft. This may be done, for example, by providing more than one optical device

102_1, 102_2, per spacecraft. An example is illustrated in Fig. 1B, where a plurality of spacecraft 108A-108E each comprise four optical devices, two optical devices 102_1 for transmitting signal 104 and receiving signal 106, and two optical devices 102_2 for transmitting signal 106 and receiving signal 104. Each optical device 102_1 of a given spacecraft 108A-108E is aligned with an optical device 102_2 of a neighboring spacecraft 108A-108E for propagating signals 104, 106 therebetween. The spacecraft 108A-108E may form part of a larger network 110 (or constellation) through which signals 104, 106 can travel.

[0027] In some embodiments, the spacecraft 108A-108E may form a closed network 120, where spacecraft 108A acts as the primary node.. An example embodiment is illustrated in Fig. 1C. Signals 104, 106 are propagated between devices 102_1 of spacecraft 108A and devices 102_2 of spacecrafts 108B, 108C, 108D, 108E along respective optical paths.

[0028] In some embodiments, the optical device is itself configured for propagating and capturing pairs of multi-wavelength signals collinearly in free space in opposite directions along multiple optical paths. An example embodiment is illustrated in Fig. 1D. Signals 104, 106 are propagated between device 102_3 of spacecraft 108A and device 102_2 of spacecraft 108B along a first optical path. Signals 104, 106 are propagated between device 102_3 of spacecraft 108A and device 102_2 of spacecraft 108C along a second optical path. In addition, signals 104, 106 are propagated between device 102_3 of spacecraft 108A and device 102_1 of spacecraft 108D along a third optical path, but signal 104 is incoming to spacecraft 108A and signal 106 is outgoing from spacecraft 108A. And finally, a third multi-wavelength signal 112 and a fourth multi-wavelength signal 114 are propagated between device 102_3 of spacecraft 108A and device 102_4 of spacecraft 108E. Signal 112 is composed of a third set of wavelengths $[\lambda_1, \ldots \lambda_p]$ that are mutually exclusive from a fourth set of wavelengths $[\lambda_1, \ldots \lambda_q]$ of which signal 114 is composed. Signals 104, 106 may differ from signals 112, 114 but do not need to be mutually exclusive therefrom.

[0029] Having the optical devices designed to communicate with each other using multi-wavelength signals enables scaling up of the communication bandwidth and/or bit rate of the network. In other words, more data may be transmitted between each spacecraft 108A, 108B and/or the data may be transmitted more quickly, than using a single wavelength signal, without significantly increasing the costs per bit of the communication. Similarly, having multiple optical devices with multi-wavelength signal capabilities per spacecraft also increases the transmission capabilities of the network and its overall capacity, at a reduced cost compared to land-based systems that use optical fiber cables and other physical connections. Although the examples illustrated herein show a spacecraft and/or or optical device configured for propagating four pairs of multi-wavelength signals, it will be understood that more or less than four pairs of multi-wavelength signals may be used.

[0030] Referring to Fig. 2, there is illustrated an example embodiment of the optical device 102_1. A transmitter 204 generates the first multi-wavelength signal 104. A receiver 206 detects the second multi-wavelength signal 106. The transmitter 204 and receiver 206 are operatively connected to a processing device 208, which may be an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA), a Digital Signal Processor (DSP), or any other type of processor. The processing device 208 may be optical or electrical, and designed for at least one of rebooting a signal, conditioning a signal, and performing calculations based on the signal. Although illustrated as separate from the optical device 102_1, the processing device 208 may form part of the optical device 102_1. In some embodiments, the transmitter 204 and receiver 206 are co-located on a substrate with the processing device 208. In this case, they may be co-packaged. Alternatively, the transmitter 204 and receiver 206 are provided on one or more substrates that are separate from the processing device 208, but in close proximity thereto. The processing device 208 may be used to drive optical emitters in the transmitter 204 and process data received by photodetectors in the receiver 206. In some embodiments, the processing device 208 is a passive or active switching device. The processing device 208 may be connected to the transmitter 204 and receiver 206 with, for example, parallel high-speed electrical lanes. Other embodiments may also apply, depending on practical implementations.

[0031] At least one first optical component 212 propagates the first multi-wavelength signal 104 into free space and captures the second multi-wavelength signal 106 from free space. The first optical component(s) 212 refers to one or more beam treatment optics, such as a lens or lens system. The lens may also be replaced by one or more curved mirror. Any component capable of changing the geometrical characteristics of a light beam, such as changing the beam size or beam orientation, may be used. A single set of beam treatment optics may be used to propagate the first multi-wavelength signal 104 into free space and capture the second multi-wavelength signal 106 from free space.

[0032] At least one second optical component 210 is coupled between the first optical component(s) 212 and the transmitter 204 and receiver 206. The second optical component(s) 210 are beam discriminating optics that discriminate between the first multi-wavelength signal 104 and the second multi-wavelength signal 106 and redirects the signals 104, 106 accordingly. More specifically, the second optical component 210 receives the first multi-wavelength signal

104 from the transmitter 204 and transmits the first multi-wavelength signal 104 to the first optical component 212 for propagation into free space, and receives the second multi-wavelength signal 106 from the first optical component 212 and transmits the second multi-wavelength signal 106 to the receiver 206 for detection. It will be understood that in an embodiment where the direction of the signals 104, 106 are reversed, such as in optical device 102_2, the second optical component 210 will redirect the signals 104, 106 such that the incoming signal is provided to the receiver 206 and the outgoing signal is provided to the first optical component 212.

[0033] In some embodiments, the second optical component(s) 210 may also be used to filter a beacon signal traveling within the incoming signal 106 (for example, carrying identification and/or system alignment information). A beam splitter may form part of the second optical component(s) 210 or be provided separate therefrom between the second optical component(s) 210 and receiver 206 to filter out the beacon signal and analyse its amplitude in a separate photodetector.

[0034] In some embodiments, the second optical component(s) 210 discriminates the signals 104, 106 based on wavelength. For example, the second optical component(s) 210 may be a filter, such as a dichroic filter that can be low pass or high pass. An example is illustrated in Fig. 3A, where the first multi-wavelength signal 104 is composed of four wavelengths [λ_1, λ_2, λ_3, λ_4,] and the second multi-wavelength signal 106 is composed of four wavelengths [λ_a, λ_b, λ_c, λ_d] higher than the four wavelengths [λ_1, λ_2, λ_3, λ_4,]. More or less than four wavelengths may be used. A dichroic low-pass filter allows the first multi-wavelength signal 104 through and blocks the second multi-wavelength signal 106. A dichroic high-pass filter may instead be used to let the second multi-wavelength signal 106 through while blocking the first multi-wavelength signal 104. In some embodiments, the wavelengths of the first and second signals 104, 106 are interleaved, as illustrated in the example of Fig. 3B. In this case, a multiband bandpass filter may be used to allow either one of the signals 104, 106 through while blocking the other one of the signals 104, 106.

[0035] Other embodiments for the second optical component(s) 210 to discriminate between the two signals 104, 106 are also considered. For example, the second optical component(s) 210 may be a beam splitter, with a ratio of reflection to transmission set as a function of the wavelengths of the respective signals 104, 106, and the objective of transmitting or reflecting a given one of the signals 104, 106. In another example, the second optical component(s) 210 is a polarizing beam splitter that discriminates between the two signals 104,106 based on polarization direction. For example, one of signals 104, 106 may have a vertical polarisation and the other one of signals 104, 106 may have a horizontal polarization. It will be understood that various discriminating optics may be used to distinguish between the two signals 104, 106, using one or a combination of components.

[0036] The embodiments described herein, wherein an optical device is configured for bi-directional, multi-wavelength, multiband communication in free space, result in significant cost savings due at least to low component count for increased bandwidth and/or bit rate, compared to a single wavelength signals. Decreasing the component count allows a reduction in the volume and mass of payloads, thus reducing the overall costs associated with putting such spacecraft in space or in orbit. The low component count is also a result of the sharing of the second optical component(s) 210, for discriminating between the first multi-wavelength signal and the second multi-wavelength signal, and the sharing of the first optical component(s) 212, for coupling the multi-wavelength signals into and out of the optical device. This helps to keep the system lightweight and keeps the power losses and/or power consumption low, due to the reduced instances of frequency conversion.

[0037] Referring to Fig. 4, there is illustrated an example embodiment for the at least one second optical component(s) 210. A wavelength separator 302, which may be a multiband filter, discriminates between the first multi-wavelength signal 104 and the second multi-wavelength signal 106. A mirror 304 reflects the first multi-wavelength signal 104 towards the wavelength separator 302. In some embodiments, the multi-wavelength signal 104 is amplified through an amplifier 310 before being propagated into free space. The amplifier 310 can be positioned downstream from the wavelength separator 302, as illustrated, or upstream from the wavelength separator 302, before being transmitted to the first optical component(s) 212. The amplifier 310, may be any type of amplifier suited for amplification of the first multi-wavelength signal 104, such as but not limited to a high power doped fiber amplifier. In some embodiments, the amplifier 310 is an Erbium-Ytterbium doped fiber amplifier (EYDFA).

[0038] The wavelength separator 302 transmits the second multi-wavelength signal 106 from the optical component 212 towards the receiver 206. In some embodiments, the second multi-wavelength signal 106 is also amplified prior to transmission to the receiver 206. An amplifier 308 may be a low noise amplifier, such as an Erbium Doped fiber amplifier (EDFA). In some embodiments, the amplifier 308 is omitted. In some embodiments, a monitoring tap is provided by sampling the second multi-wavelength signal 106 using a partially reflecting mirror or wavelength separator 306 and a photodetector 312. The monitoring tap may be used, for example, to provide a signal level proportional to the quality of the alignment of the focusing optics (i.e. first optical component(s) 212, such as a lens or lens system capturing the incoming signals 104, 106) relative to the incoming signal. In some embodiments, the wavelength separator 302 may be used to send the beacon signal to the photodetector 312.

[0039] Reference is made to Figs. 5A-5B to describe various example embodiments of the transmitter 204 and receiver 206. As shown in Fig. 5A, the processing device 208 may be used to drive optical emitters 504, such as lasers, through a laser driver 502. The laser driver 502 converts differential high speed signals from the processing device 208 into a unique signal provided to each of the optical emitters 504. The example is shown with four optical emitters in order to generate a first multi-wavelength signal 104 composed of four wavelengths, but more or less optical emitters 504 may be used. The optical emitters 504 each have their center wavelength located within a given wavelength range. In some embodiments, the wavelength range is selected to be suitable for amplification.

[0040] In some embodiments, the optical emitters 504 may be directly modulated side emitting lasers, which are coupled to a wavelength division multiplexer 506 for outputting the first multi-wavelength signal 104. The wavelength division multiplexer 506 may take various forms, such as but not limited to an arrayed waveguide, an echelle grating on silicon photonics (or other type of integrated circuit), or a plurality of discrete dichroic filters or diffraction grating mirrors. Furthermore, although illustrated as part of the transmitter 204, the wavelength division multiplexer 506 may be external therefrom, for example as part of the at least one second optical component(s) 210 or as a separate component provided between the transmitter 204 and the at least one second optical component(s) 210. In some embodiments, an additional optical emitter 508 is used to provide a beacon signal, for example to add identification and/or system alignment information to the first multi-wavelength signal 104. The additional optical emitter 508 may be a low speed laser and differ from the optical emitters 504. The additional optical emitter 508 may also be omitted.

[0041] In the example illustrated in Fig. 5A, the second multi-wavelength signal 106 is received at the receiver 206 through a wavelength division de-multiplexer 510, where the signal 106 is de-multiplexed and sent to a plurality of photodetectors 512. The de-multiplexer 510 may also be provided externally to the receiver 206, as part of the at least one second optical component(s) 210 or as a separate component between the receiver 206 and the at least one second optical component(s) 210. The de-multiplexer 510 may be, for example, an arrayed waveguide, an echelle grating on silicon photonics (or other type of integrated circuit), a plurality of discrete dichroic filters or diffraction grating mirrors, or a multimode interference filter. The received signal 106 gets separated through the optical de-multiplexer 510 and sent to discrete photodetectors 512 that will each generate a current proportional to the light intensity received from DWDM 510. Four photodetectors 512 are shown for a four wavelength signal 106 but more or less photodetectors 512 may be used. In some embodiments, the current is transformed into a voltage through a trans-impedance amplifier 514. The voltage may then be transformed into high speed differential signals that are sent to the processing device 208.

[0042] In the embodiment of Fig. 5A, the optical emitters 504 may be distributed feedback Bragg (DFB) side emitters, where single mode signals are directly modulated, leading to modulation speeds in excess of 10 Gbps. In some embodiments, the optical emitters 504 are wavelength tunable vertical-cavity surface-emitting lasers (VCSELs), which can be directly modulated. Alternatively, and as shown in Fig. 5B, the optical emitters 504 are single mode lasers operated in a constant power mode and are modulated by Mach-zehnder modulators (MZM) 516 operated by a driver 518. The MZM 516 may be integrated on a photonics integrated circuit. The modulated light may then be combined into the first multi-wavelength signal 104 through the multiplexer 506.

[0043] It will be understood that various embodiments may be used for the receiver 204 and/or transmitter 206. For example, the laser driver 502 may be replaced with a simple analog circuit having a bias tee. The bias tee's voltage can be adjusted or driven by the processing device 208 (i.e. an ASIC or processor signal). The MZM 516 may be replaced with electro-absorption modulators (EML) or omitted. Other embodiments are also considered.

[0044] Referring to Fig. 6, there is shown an example embodiment of a spacecraft 108 having a processing device 208, which may be an ASIC, an FPGA, a DSP, or another type of processor, shared by a plurality of optical devices 102. Each optical device 210 is configured to capture and receive two mutually exclusive multi-wavelength signals that propagate collinearly in free space. Each optical device 210 routes the captured multi-wavelength signal to a set of photodetectors. In some embodiments, the received signals are amplified before being routed to a de-multiplexer and then sent to photodetectors. Alternatively, signals can be routed to the de-multiplexer without amplification, for example when using highly sensitive photodetectors such as avalanche photodetectors.

[0045] The architecture illustrated in Fig. 6, whereby the optical devices 210 are provided in close proximity to the processing device 208, results in having short paths between the optical devices 210 and the processing device 208, thus reducing losses which in turn helps decrease the power consumption of each spacecraft and of a communication network composed of such spacecraft. Reduced power consumption can allow extended lifespan and/or mission duration for the spacecraft. The sharing of the processing device 208 amongst the plurality of optical devices 210 decreases the component count normally needed for traditional satellite architectures, where multiple electro-optic conversions occur from end to end of a system.

[0046] Referring to Fig. 7A, there is illustrated an example embodiment for the first optical component(s) 212, i.e. the beam treatment optics. The incoming multi-wavelength signal 106 is reflected by a mirror 706 onto a convex reflector 704. The reflected signal 106 travels through a lens 702 at position P1. This signal 106 will then travel to the beam discriminating optics of the second optical component(s) 210. The same components may be used for outgoing multi-wavelength signal 104, as illustrated in the example of Fig. 7B. The multi-wavelength signal 104 coming from the beam discriminating optics of the second optical component(s) 210 travels through the lens 702, is reflected by the convex reflector 704 onto the mirror 706 and out of the optical device 102.

[0047] In some embodiments, component count for the optical device 102 may be further reduced by using the incoming data communication multi-wavelength signal 106 to optimise alignment of the beam treatment optics, instead of using a beacon signal which requires a separate detector (i.e. photodetector 312). For example, and with reference to Fig. 7C, a translating stage 708 may be used to translate the lens 702 along direction A from position P1 to position P2. With the lens at position P2, the incoming beam has a radius of R2 and can be used for beam alignment when the system is in an alignment mode. The lens 702 is returned to position P1 when the system is in a data transfer mode. This embodiment would allow the wavelength separator 306 and photodetector 312 from the beam discriminating optics to be omitted, thus reducing overall component count and reducing insertion losses, leading to greater transmission efficiency and lower power consumption.

[0048] In some embodiments, the optical device 102 is a Silicon Photonics (SiP) inter-satellite link optical generator and receiver capable of communication speeds in excess of 200 Gbps. The laser emitter speeds may be scaled instead of increasing the actual wavelength channel count in order to obtain desirable size, weight and power characteristics for the device 102.

[0049] In one specific and non-limiting example, discrete DFB lasers are coupled to SiP-based Mach-Zehnder modulators. The modulated signals are multiplexed by an SiP-based wavelength division multiplexer and the combined signal is amplified by an EDFA or EYDFA. The amplified signal is them passed through beam treatment optics for propagating into free space. Such a system offers modulation up to 50 Gbps per channel.

[0050] The above description is meant to be exemplary only, and one skilled in the art will recognize that changes may be made to the embodiments described without departing from the scope of the invention disclosed. Still other modifications which fall within the scope of the present invention will be apparent to those skilled in the art, in light of a review of this disclosure.

[0051] Various aspects of the systems and methods described herein may be used alone, in combination, or in a variety of arrangements not specifically discussed in the embodiments described in the foregoing and is therefore not limited in its application to the details and arrangement of components set forth in the foregoing description or illustrated in the drawings. For example, aspects described in one embodiment may be combined in any manner with aspects described in other embodiments. Although particular embodiments have been shown and described, it will be apparent to those skilled in the art that changes and modifications may be made without departing from this invention in its broader aspects. The scope of the following claims should not be limited by the embodiments set forth in the examples, but should be given the broadest reasonable interpretation consistent with the description as a whole.

CLAIMS

1. An optical device for inter-spacecraft communication comprising:

a first transmitter for generating a first multi-wavelength signal composed of a first set of wavelengths;

a first receiver for detecting a second multi-wavelength signal composed of a second set of wavelengths mutually exclusive from the first set of wavelengths;

at least one first optical component configured for propagating the first multi-wavelength signal into free space and for capturing the second multi-wavelength signal from free space, the first and second multi-wavelength signals propagating collinearly in free space in opposite directions; and

at least one second optical component coupled between the first transmitter, the first receiver, and the at least one first optical component, and configured for discriminating between the first multi-wavelength signal and the second multi-wavelength signal and redirecting the first multi-wavelength signal to the at least one first optical component and the second multi-wavelength signal to the first receiver.

2. The optical device of claim 1, further comprising:

a second transmitter for generating the second multi-wavelength signal;

a second receiver for detecting the first multi-wavelength signal;

at least one third optical component configured for propagating the second multi-wavelength signal into free space and for capturing the first multi-wavelength signal from free space; and

at least one fourth optical component coupled between the second transmitter, the second receiver, and the at least one third optical component, and configured for discriminating between the first multi-wavelength signal and the second multi-wavelength signal redirecting the second multi-wavelength signal to the at least one third optical component and the first multi-wavelength signal to the second receiver.

3. The optical device of claims 1 or 2, wherein the first set of wavelengths are interleaved with the second set of wavelengths.

4. The optical device of any one of claims 1 to 3, further comprising at least one amplifier for amplifying the first multi-wavelength signal or the second multi-wavelength signal.

5. The optical device of any one of claims 1 to 4, wherein the at least one second optical component comprises at least one filter for discriminating between the first multi-wavelength signal and the second multi-wavelength signal based on wavelength.

6. The optical device of any one of claims 1 to 4, wherein the at least one second optical component comprises at least one polarization beam splitter for discriminating between the first multi-wavelength signal and the second multi-wavelength signal based on polarization direction.

7. The optical device of any one of claims 1 to 6, wherein the first transmitter and the first receiver are co-located on a substrate with a processing device.

8. The optical device of claim 7, wherein the processing device is one of an Application Specific Integrated Circuit, a Field Programmable Gate Array, and a Digital Signal Processor (DSP).

9. The optical device of any one of claims 1 to 8, wherein the first transmitter comprises a plurality of single mode vertical-cavity surface-emitting lasers (VCSELs) driven by a laser driver.

10. The optical device of any one of claims 1 to 8, wherein the first transmitter comprises a plurality of single mode lasers operated in constant power mode and a plurality of corresponding Mach-Zehnder modulators for modulating light generated by the single mode lasers.

11. The optical device of any one of claims 1 to 10, wherein the at least one first optical component comprises a lens mounted to a translating stage for forming beams from the second multi-wavelength signal of varying radii.

12. A method for inter-spacecraft optical communication, the method comprising:

generating, at a first optical device, a first multi-wavelength signal composed of a first set of wavelengths;

propagating the first multi-wavelength signal into free space from the first optical device;

capturing from free space, at the first optical device, a second multi-wavelength signal composed of a second set of wavelengths mutually exclusive from the first set of wavelengths, the first and second multi-wavelength signals propagating collinearly in free space in opposite directions along an optical path;

detecting the second multi-wavelength signal at the first optical device; and discriminating between the first multi-wavelength signal and the second multi-wavelength signal at the first optical device and redirecting the first multi-wavelength signal for the propagating and the second multi-wavelength signal for the detecting.

13. The method of claim 12, wherein the first set of wavelengths are interleaved with the second set of wavelengths.

14. The method of claims 13 or 13, further comprising amplifying at least one of the first multi-wavelength signal and the second multi-wavelength signal.

15. The method of any one of claims 12 to 14, wherein discriminating between the first multi-wavelength signal and the second multi-wavelength signal comprises discriminating based on wavelength.

16. The method of any one of claims 12 to 15, wherein discriminating between the first multi-wavelength signal and the second multi-wavelength signal comprises discriminating based on polarization direction.

17. The method of any one of claims 12 to 16, further comprising:

generating, at a second optical device, the second multi-wavelength signal;

propagating the second multi-wavelength signal into free space from the second optical device;

capturing from free space, at the second optical device, the first multi-wavelength signal;

detecting the first multi-wavelength signal at the second optical device; and

discriminating between the first multi-wavelength signal and the second multi-wavelength signal at the second optical device and redirecting the second multi-wavelength signal for the propagating and the first multi-wavelength signal for the detecting.

18. The method of claim 17, wherein the first optical device and the second optical device are on a same spacecraft.

19. The method of claim 17, wherein the first optical device is on a first spacecraft and the second optical device is on a second spacecraft.

20. The method of claim 19, wherein the first spacecraft is a satellite and the second spacecraft is a rover or communication tower.

21. The method of claim 19, wherein the first spacecraft and the second spacecraft are part of a constellation of spacecraft.

22. The method of any one of claims 12 to 21, further comprising aligning optical components of the optical device using the second multi-wavelength signal.

23. A network of spacecraft, each of the spacecraft having at least one optical device in accordance with the optical device of anyone of claims 1 to 11, for establishing bi-directional inter-spacecraft optical communication in the network.

24. A spacecraft comprising at least one optical device in accordance with the optical device of any one of claims 1 to 11.

25. The spacecraft of claim 24, wherein the at least one optical device comprises a plurality of optical devices.

26. The spacecraft of claim 25, wherein the plurality of optical devices share a processing device.

27. The spacecraft of claim 26, wherein the transmitter and receiver of the optical devices and the processing device are co-located on a substrate.

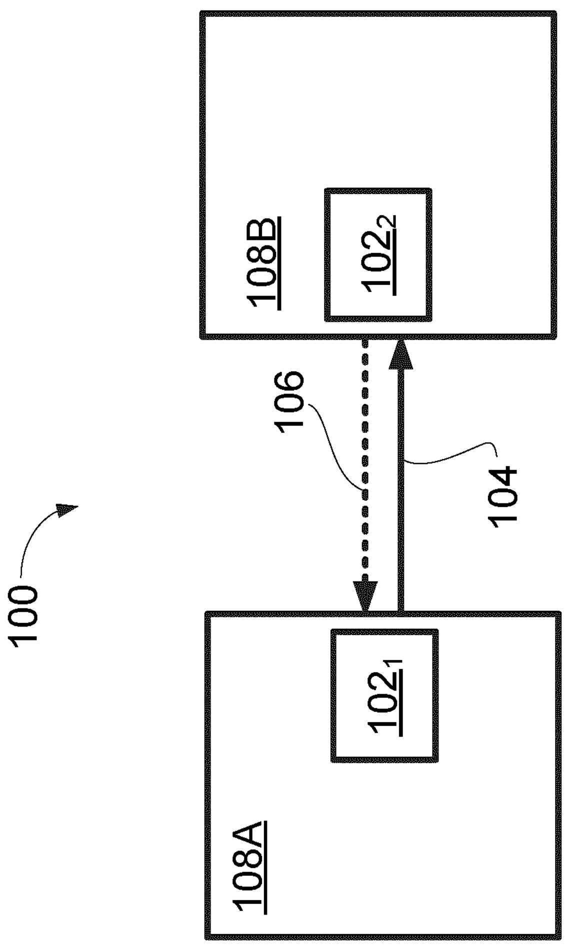


FIG. 1A

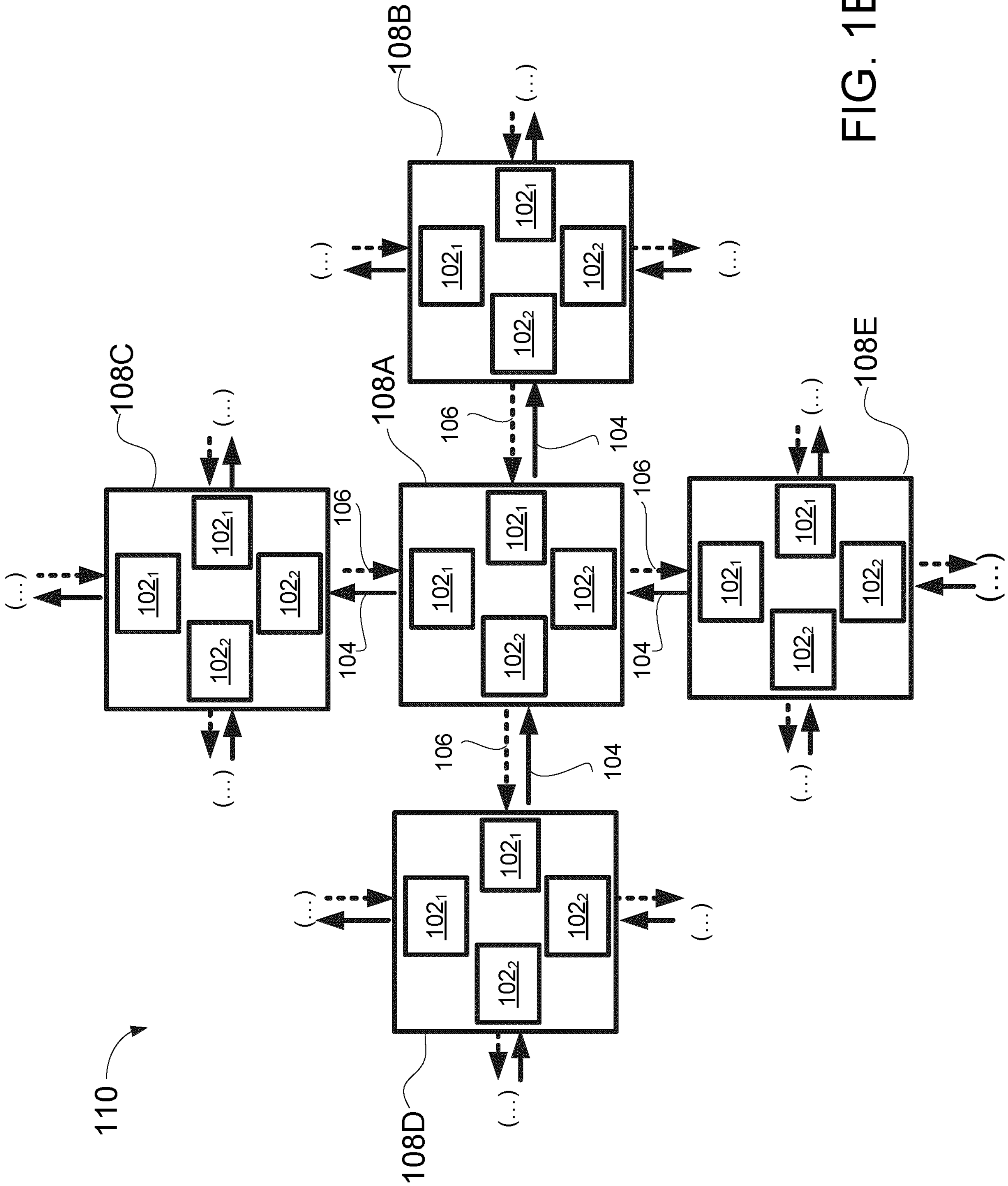
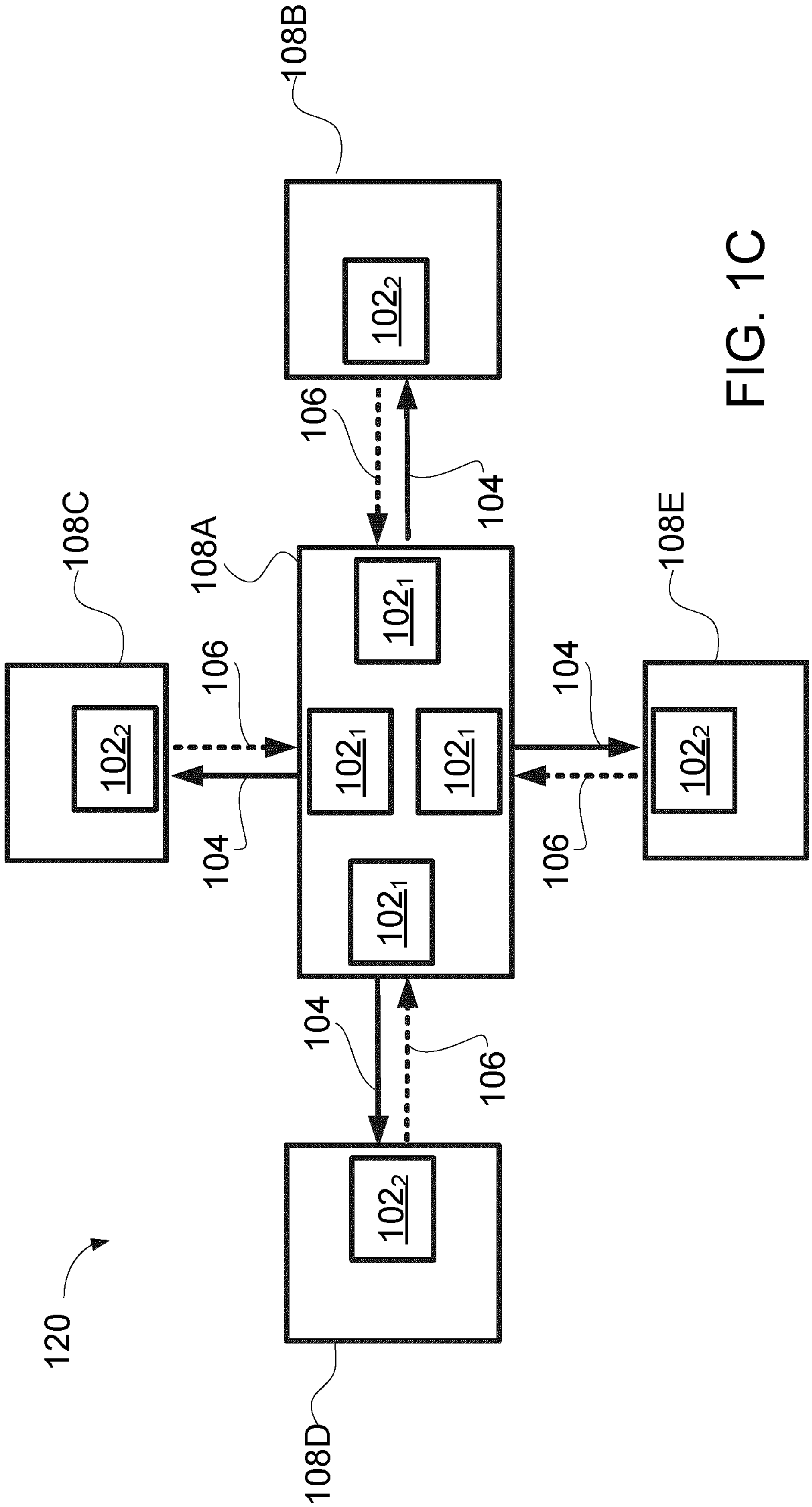


FIG. 1B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102_1
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104
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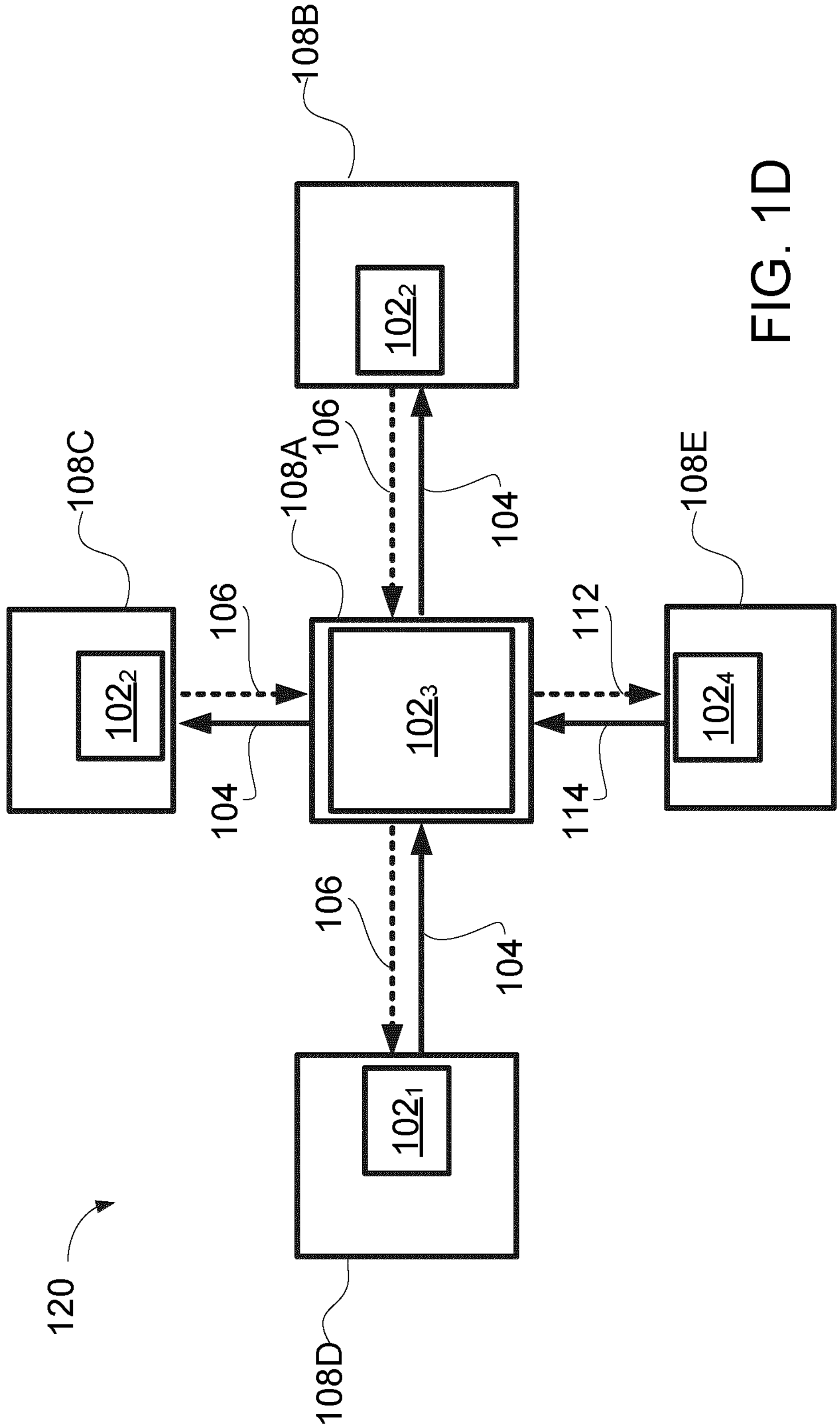
102_2
104
106
102_2
108D
120

FIG. 1C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108D

FIG. 1D

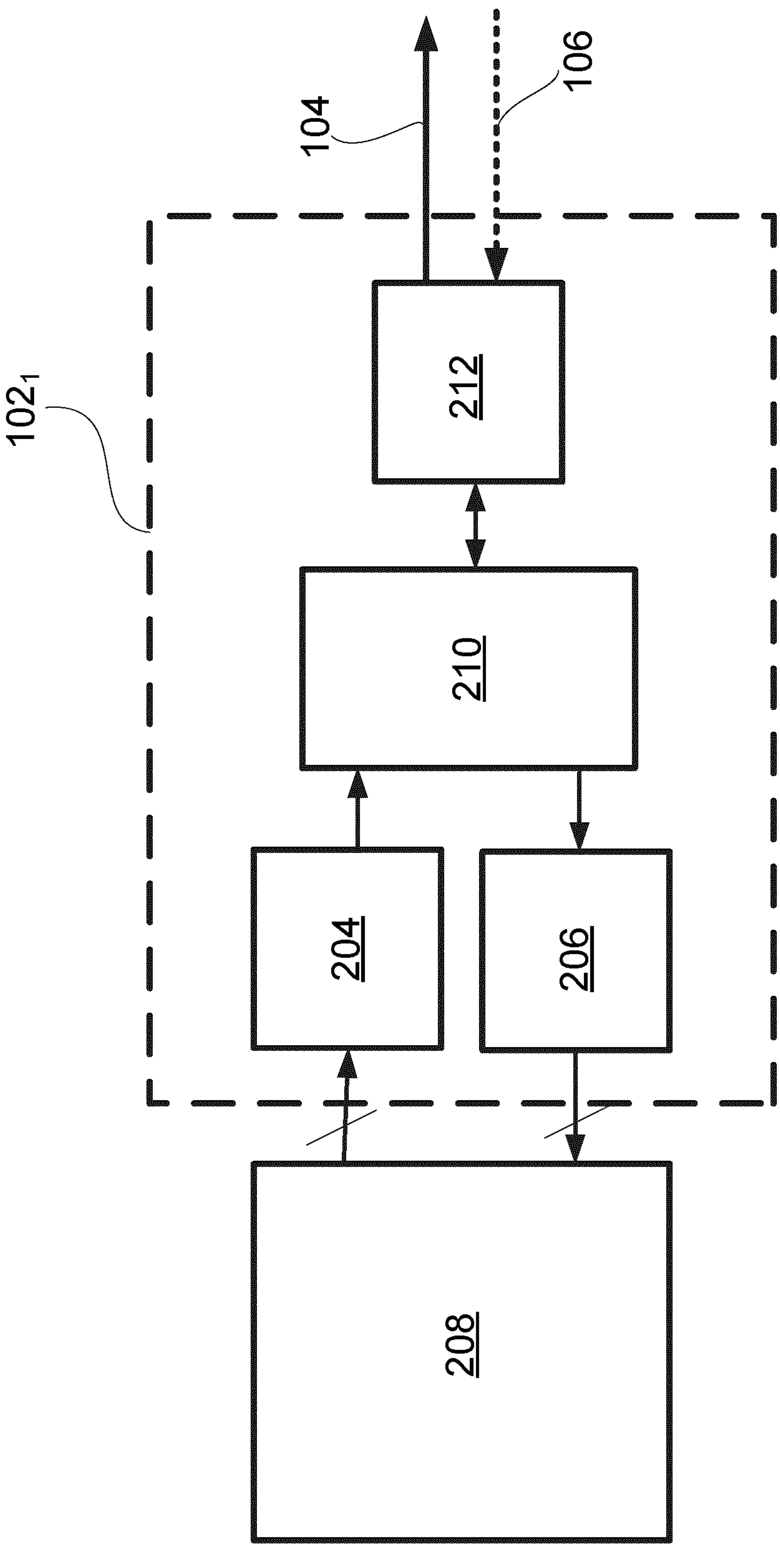


FIG. 2

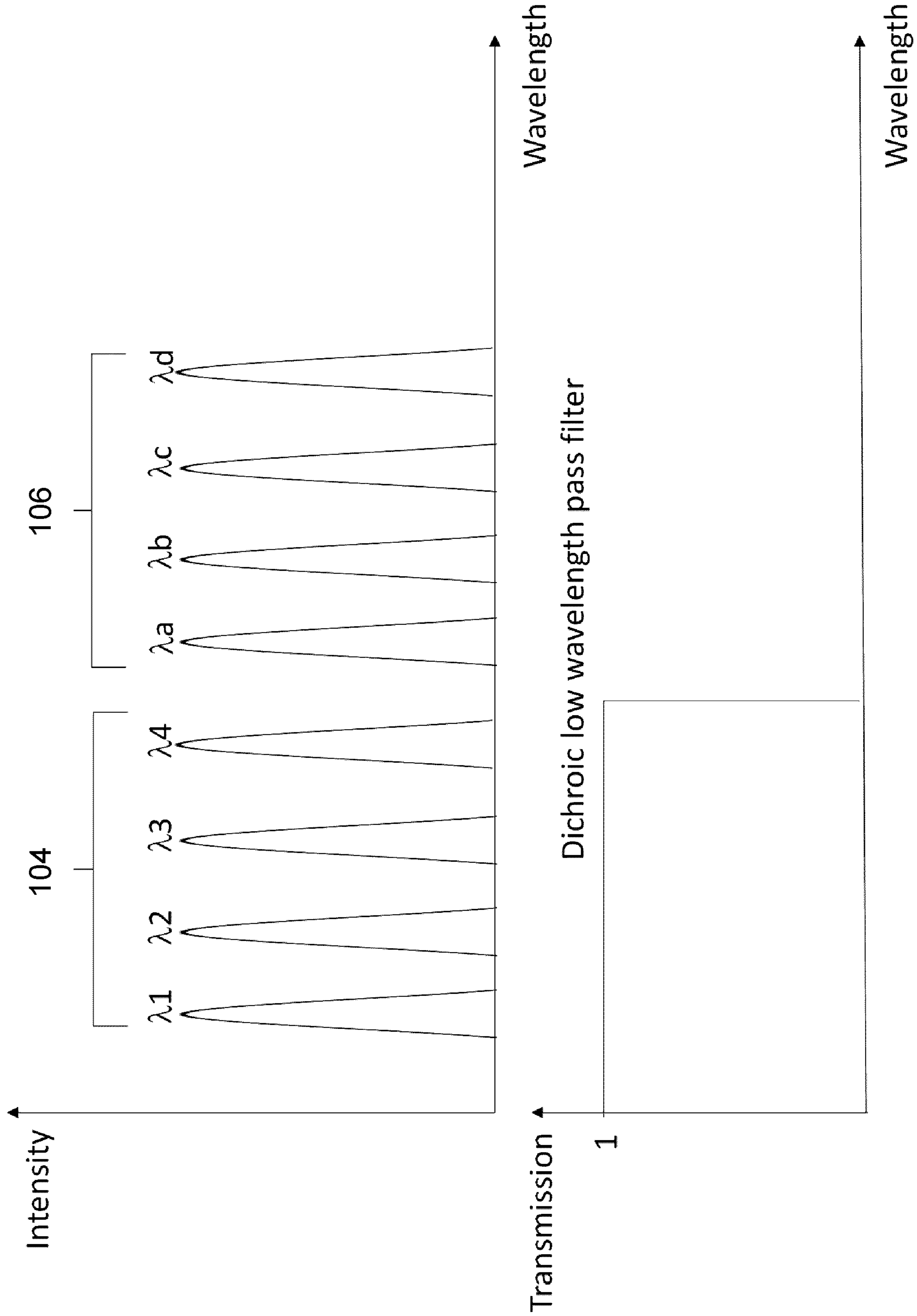
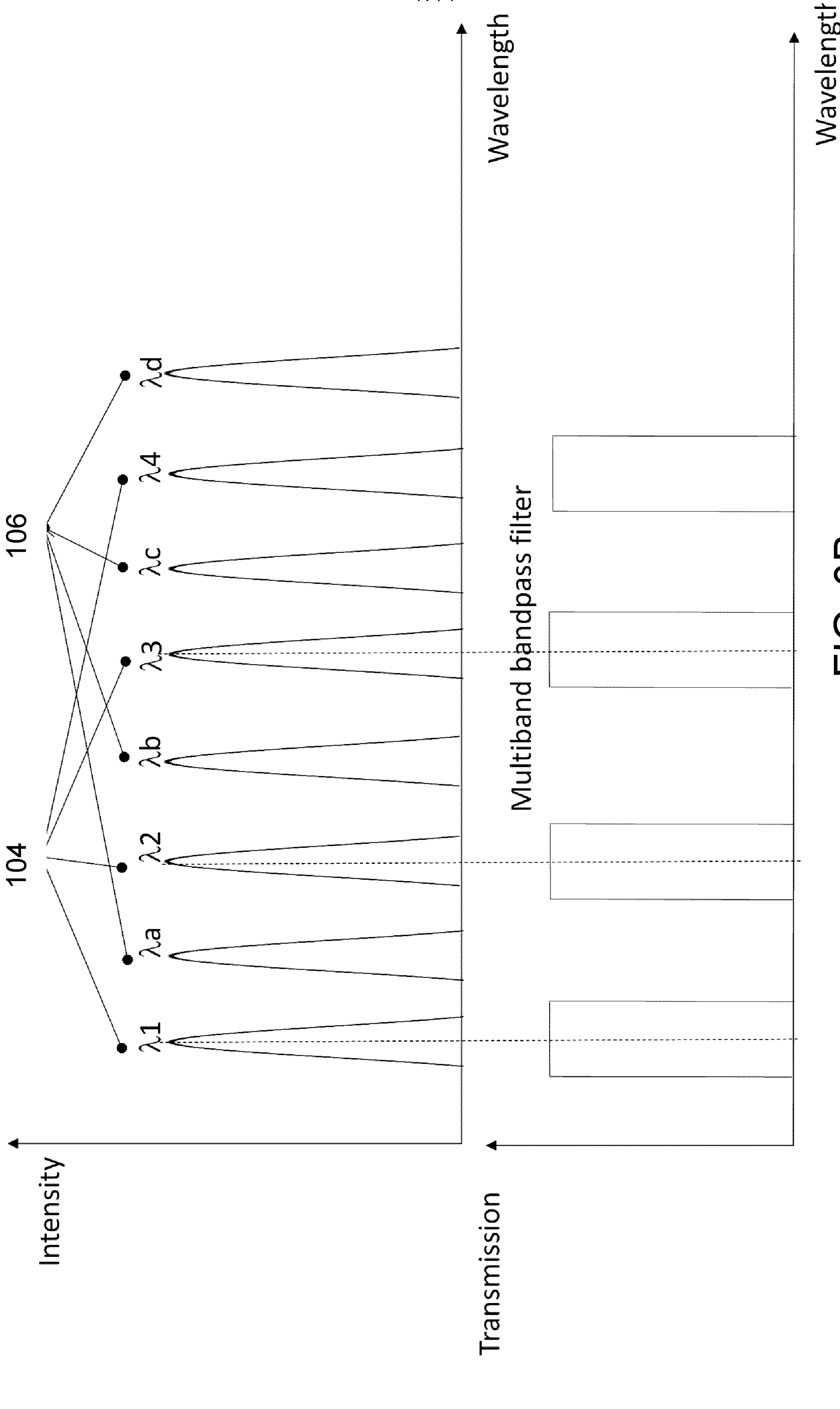

Intensity
Wavelength
104
106
λ1
λ2
λ3
λ4
λa
λb
λc
λd
Transmission
1
Wavelength
Dichroic low wavelength pass filter

FIG. 3A


Intensity
Wavelength
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106
λ1
λa
λ2
λb
λ3
λc
λ4
λd
Multiband bandpass filter
Transmission
Wavelengtl

FIG. 3B

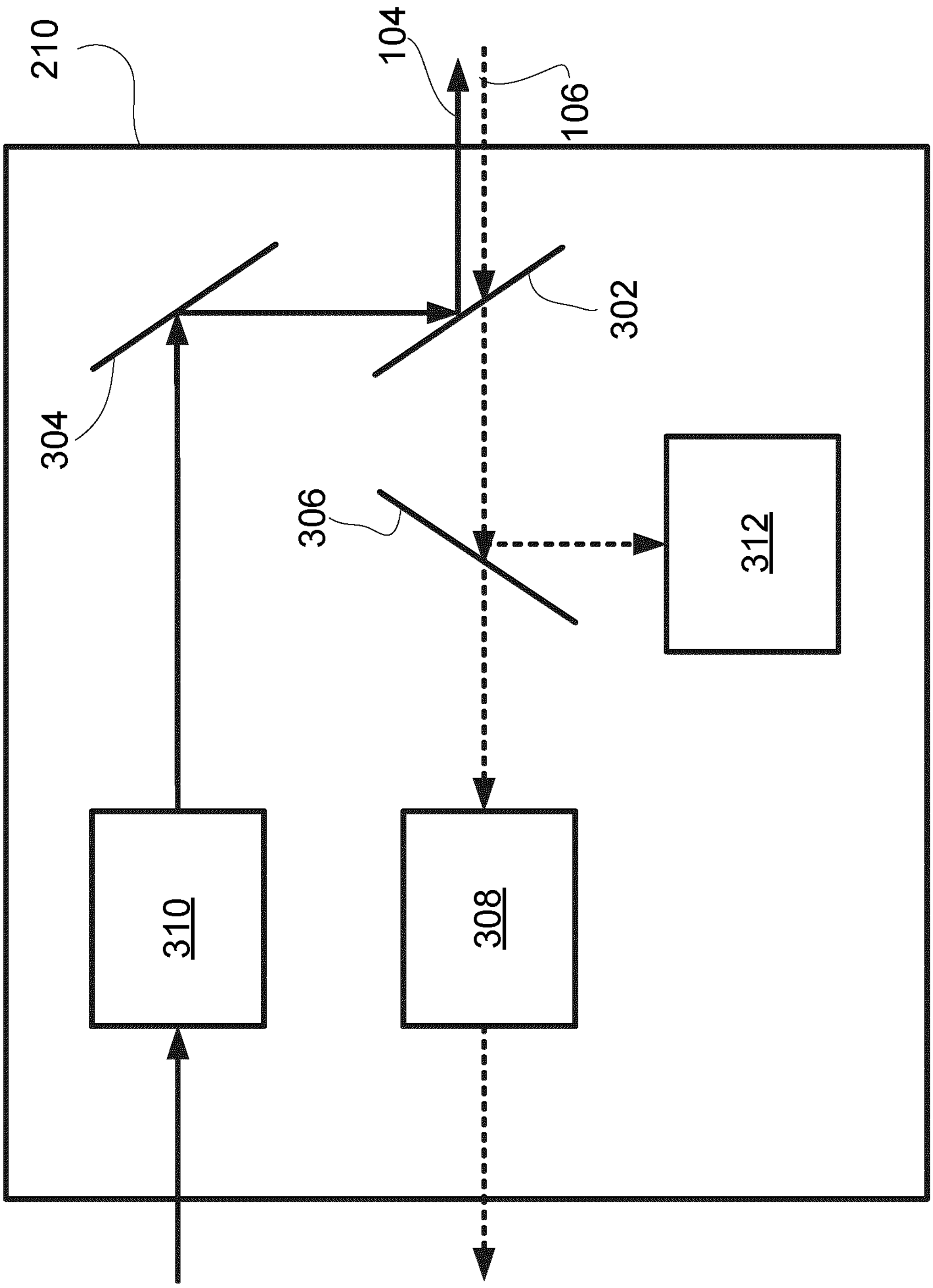
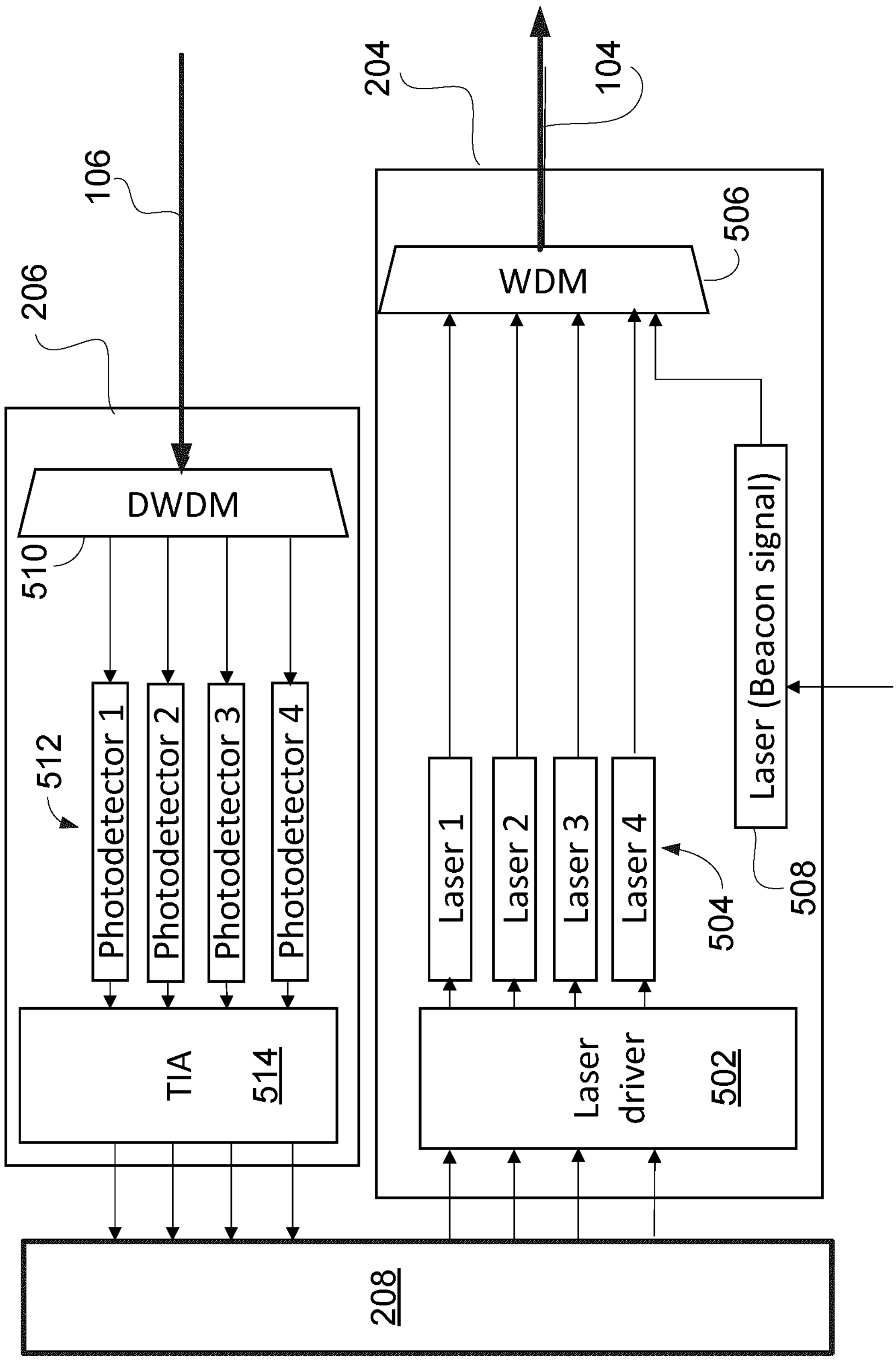


FIG. 4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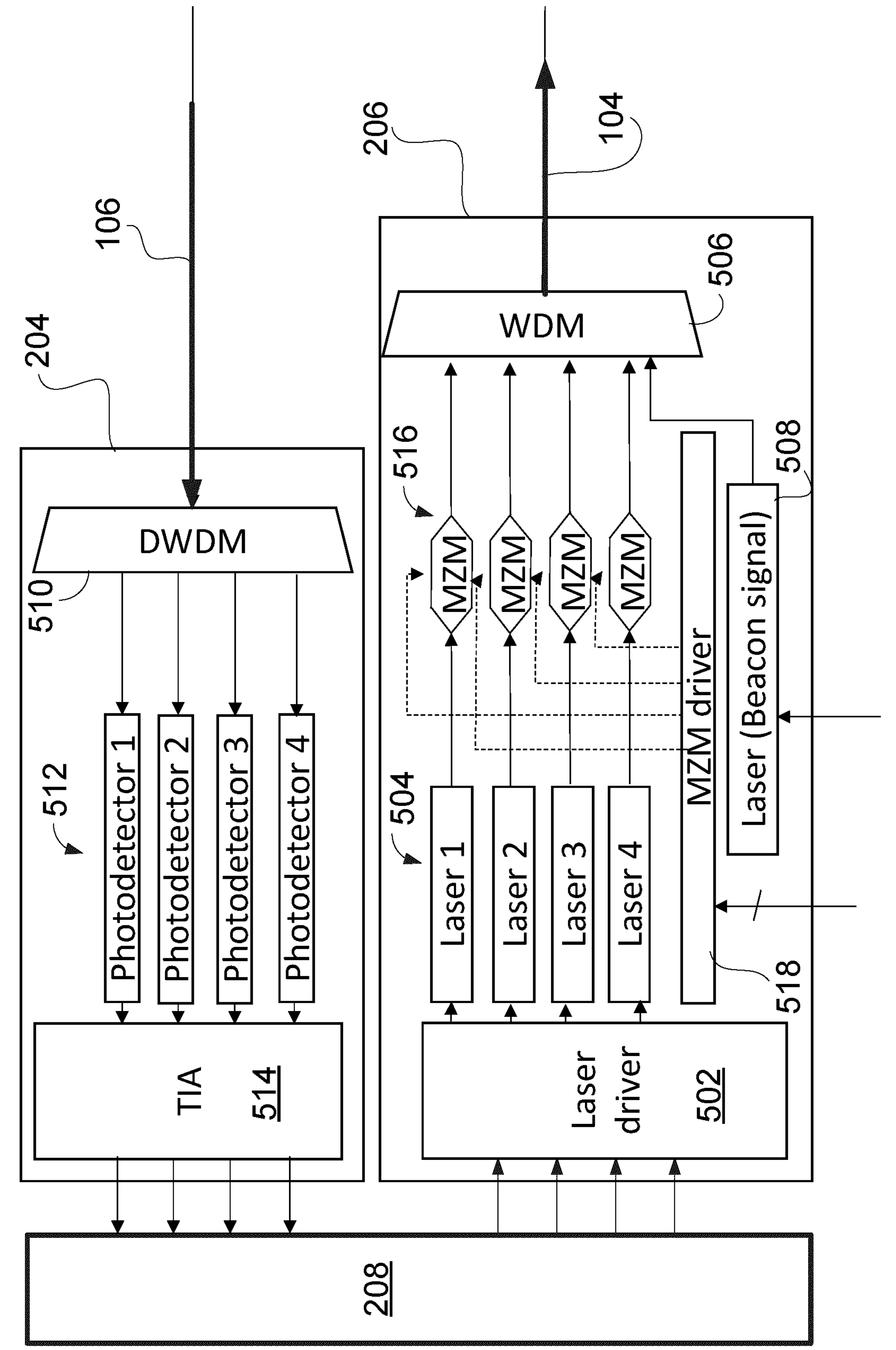
206
DWDM
510
Photodetector 1
Photodetector 2
Photodetector 3
Photodetector 4
512
TIA
514
204
104
WDM
506
Laser 1
Laser 2
Laser 3
Laser 4
504
Laser (Beacon signal)
508
Laser driver
502
208

FIG. 5A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204
WDM
506
516
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MZM
MZM
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512
Photodetector 1
Photodetector 2
Photodetector 3
Photodetector 4
504
Laser 1
Laser 2
Laser 3
Laser 4
MZM driver
Laser (Beacon signal)
518
TIA
514
Laser
driver
502
208

FIG. 5B

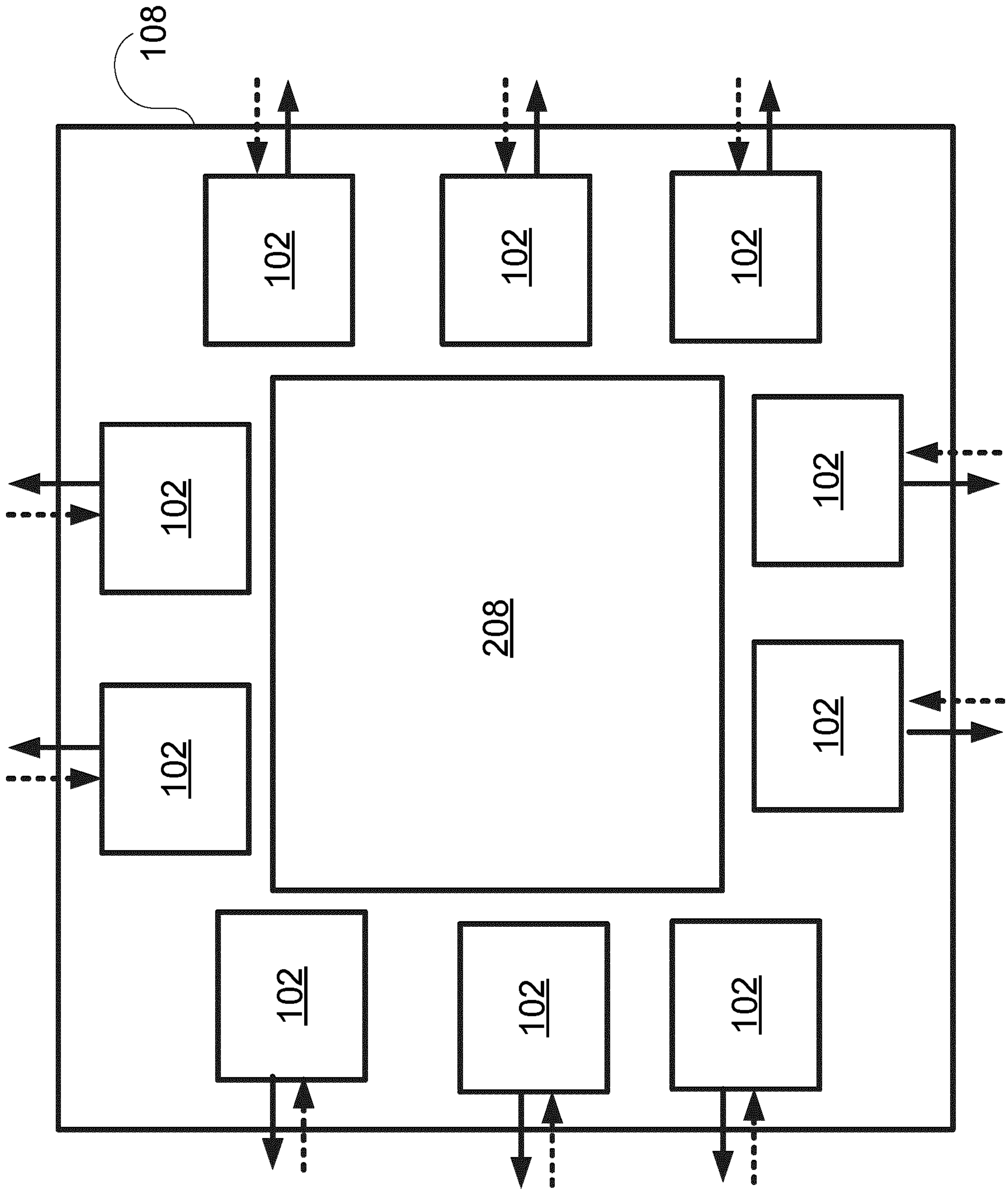

FIG. 6

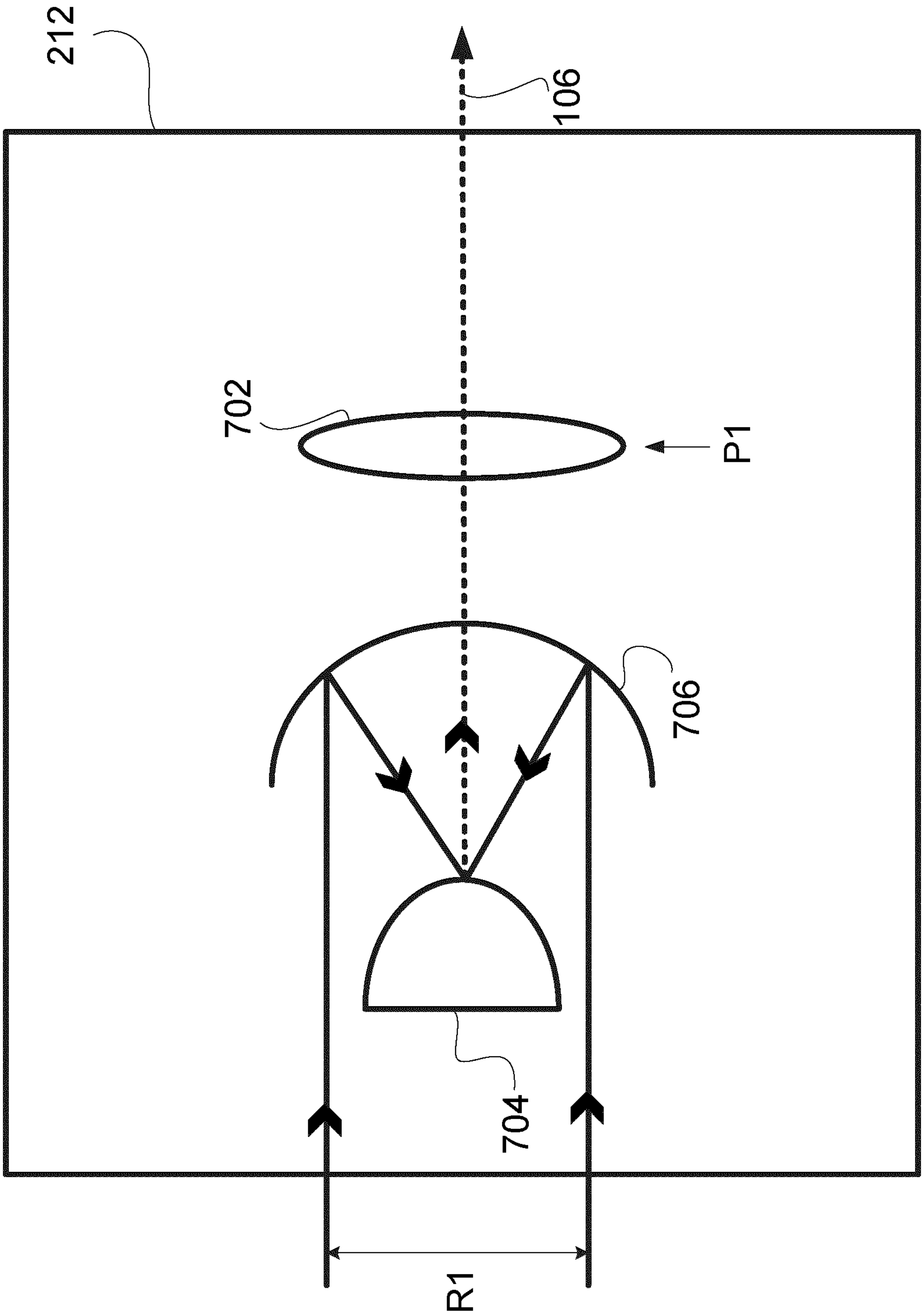

FIG. 7A

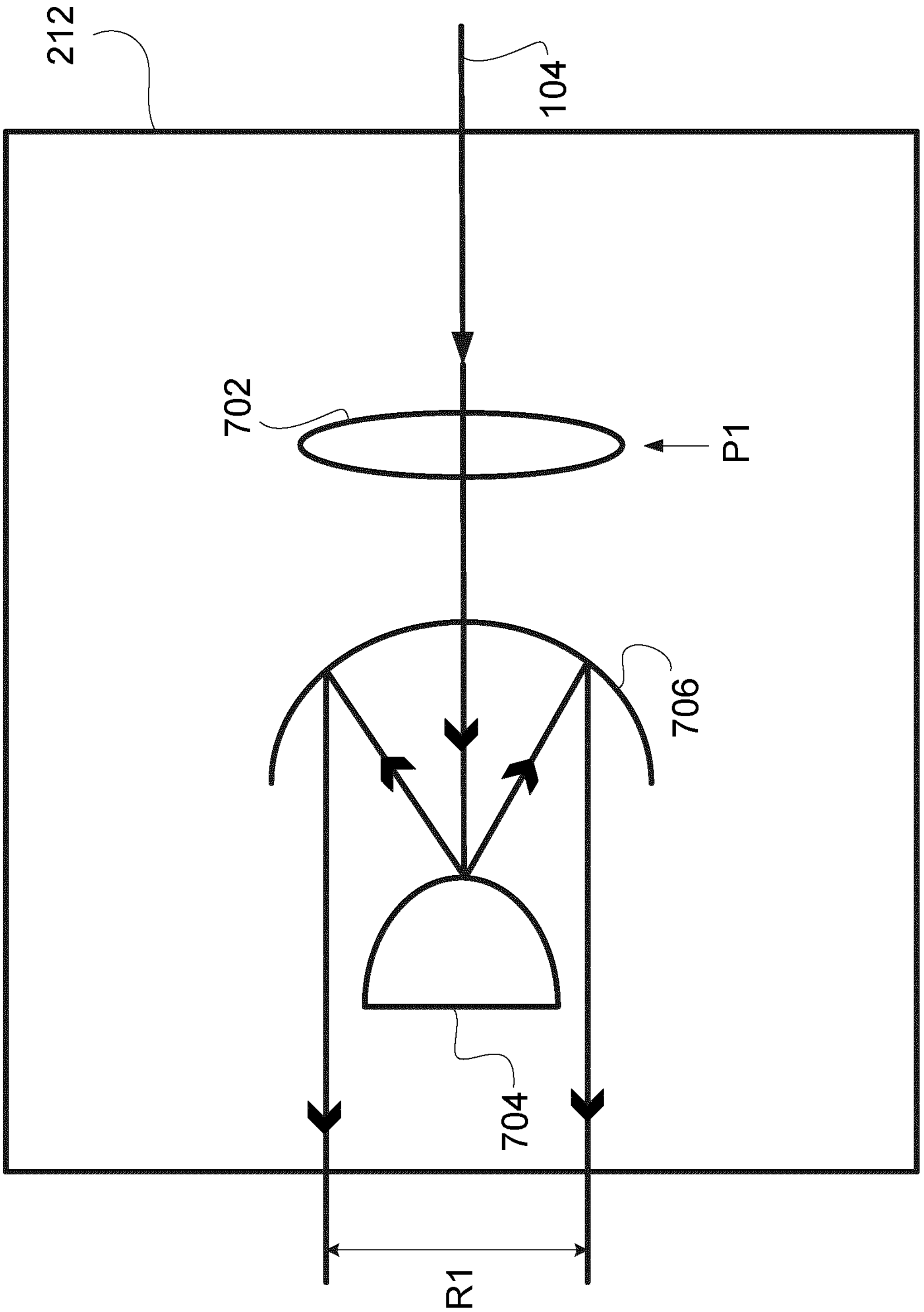

FIG. 7B

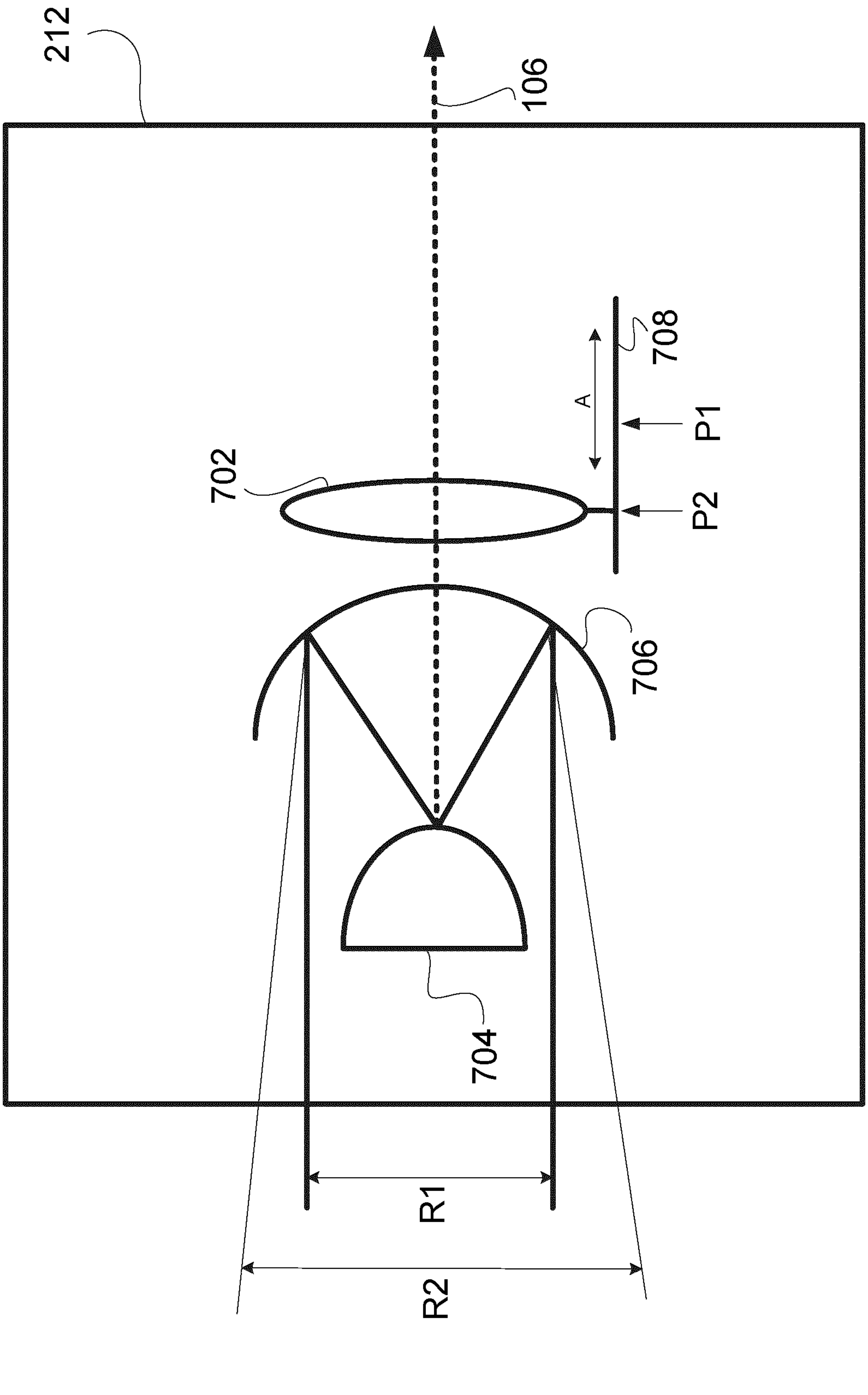

FIG. 7C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2021/050144

A. CLASSIFICATION OF SUBJECT MATTER
IPC: **H04B 10/112** (2013.01) , ***G02B 27/10*** (2006.01) , ***G02B 5/20*** (2006.01) , ***G02B 7/02*** (2021.01) , ***H01L 31/12*** (2006.01) , ***H04B 10/40*** (2013.01) (more IPCs on the last page)

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)
All IPC with keyword search

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

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Database: Orbit Questel
Keywords: inter, satellite/spacecraft/spaceship/space shuttle; optical/light/laser, communication, multi wavelength/frequency/band/bandwidth, transmitter/receiver/transceiver, discriminate/filter/separate/segregate/diplexer, relay

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 9,042,734 B2 (Makowski et al.) 26 May 2015 (26-05-2015) Abstract; Figs. 1, 3 to 5; Cols. 1 to 5, 7 to 9; claims 1 to 4	1 to 21, 23 to 27
Y	CN 109889252 A (Hou et al.) 14 June 2019 (14-06-2019) Abstract; pages 3 to 4	1 to 21, 23 to 27
Y	CN 105871499 B (wang et al.) 3 July 2018 (03-07-2018) Abstract; pages 6 to 7, 9, 10; Figs. 1, 3, 4	1 to 21, 23 to 27
Y	WO 2014/103231 A1 (Satoh et al.) 3 July 2014 (03-07-2014) Abstract	10
A	US 8,913,894 B2 (Coleman et al.) 16 December 2014 (16-12-2014) The whole document	1 to 27

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

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"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
"D"	document cited by the applicant in the international application	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"E"	earlier application or patent but published on or after the international filing date	"&"	document member of the same patent family
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 09 April 2021 (09-04-2021)	Date of mailing of the international search report 13 May 2021 (13-05-2021)
Name and mailing address of the ISA/CA Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 819-953-2476	Authorized officer Sara Li (819) 994-7493

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 105553539 B (Chen et al.) 18 January 2019 (18-01-2019) The whole document	1 to 27

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US9042734B2	26 May 2015 (26-05-2015)	US2014294399A1	02 October 2014 (02-10-2014)
		AU2014250066A1	05 November 2015 (05-11-2015)
		AU2014250066B2	09 June 2016 (09-06-2016)
		CN105284064A	27 January 2016 (27-01-2016)
		EP2982060A1	10 February 2016 (10-02-2016)
		EP2982060B1	26 June 2019 (26-06-2019)
		IL241895A	31 October 2018 (31-10-2018)
		JP2016519506A	30 June 2016 (30-06-2016)
		JP6204567B2	27 September 2017 (27-09-2017)
		WO2014163741A1	09 October 2014 (09-10-2014)
CN109889252A	14 June 2019 (14-06-2019)	None	
CN105871499B	03 July 2018 (03-07-2018)	CN105871499A	17 August 2016 (17-08-2016)
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US8913894B2	16 December 2014 (16-12-2014)	US2014016941A1	16 January 2014 (16-01-2014)
		CN104662820A	27 May 2015 (27-05-2015)
		CN110113102A	09 August 2019 (09-08-2019)
		EP2873172A2	20 May 2015 (20-05-2015)
		EP2873172B1	19 February 2020 (19-02-2020)
		EP3582411A1	18 December 2019 (18-12-2019)
		IL236671D0	26 February 2015 (26-02-2015)
		IL236671A	31 December 2017 (31-12-2017)
		JP2015524629A	24 August 2015 (24-08-2015)
		JP6046815B2	21 December 2016 (21-12-2016)
		US2015071645A1	12 March 2015 (12-03-2015)
		US9077449B2	07 July 2015 (07-07-2015)
		WO2014025426A2	13 February 2014 (13-02-2014)
		WO2014025426A3	28 August 2014 (28-08-2014)
		WO2014025426A8	26 February 2015 (26-02-2015)
CN105553539B	18 January 2019 (18-01-2019)	CN105553539A	04 May 2016 (04-05-2016)

H04J 14/02 (2006.01) , *H01S 5/183* (2006.01)