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(71) **Applicant: HUBER+SUHNER POLATIS LIMITED** [GB/GB]; 332-2 Cambridge Science Park, Milton Road, Cambridge Cambridgeshire CB4 0WN (GB).

(72) **Inventors: MONTGOMERY, David James**; c/o HUBER+SUHNER POLATIS LIMITED, 332-2 Cambridge Science Park, Milton Road, Cambridge Cambridgeshire CB4 0WN (GB). **WILKINSON, Peter John**; c/o HUBER+SUHNER POLATIS LIMITED, 332-2 Cambridge Science Park, Milton Road, Cambridge Cambridgeshire CB4 0WN (GB).

(74) **Agent: SLINGSBY PARTNERS LLP**; 1 Kingsway, London Greater London WC2B 6AN (GB).

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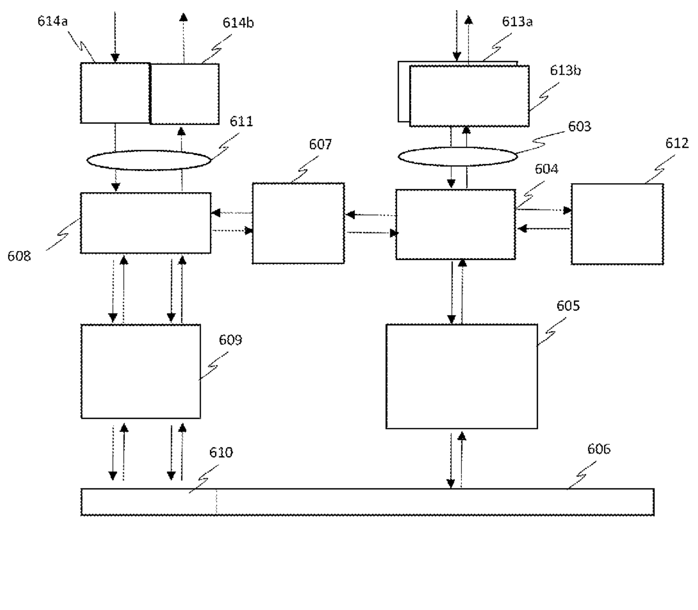

FIG. 11

(57) **Abstract:** An optical switch comprising a plurality of independently controllable systems, each independently controllable system comprising a set of input ports and a set of output ports, whereby the optical switch is optically configured such that the set of output ports can only receive data from the corresponding set of input ports, each system comprising: a set of input ports, each input port configured to transport an optical signal having at least one component frequency channel; a set of output ports corresponding to the set of input ports, each output port configured to transport an optical signal having at least one component frequency channel; a first programmable deflection plane configured to deflect beams incident thereon to form a corresponding first deflected array of beams; a second programmable deflection plane configured to deflect beams incident thereon to form a corresponding second deflected array of beams; a beam steering optical element group configured to transfer the first deflected array of beams between the first programmable

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deflection plane and the second programmable deflection plane, the beam steering optical element group of each of the plurality of systems comprising a common plane and an optical system between the common plane and the second programmable deflection plane; and wherein the optical switch is configured to form a Fourier conjugate plane in a steering direction, of the first programmable deflection plane of each of the plurality of systems on the common plane for the plurality of systems, wherein the Fourier conjugate plane of the first programmable deflection plane of one system overlaps the Fourier conjugate plane of the first programmable deflection plane of at least one other system on the common plane; and wherein the optical system is configured to form an image of each of the plurality of systems, which is a Fourier conjugate in the steering direction, of the first programmable deflection plane on the second programmable deflection plane.

OPTICAL SWITCH

BACKGROUND

Optical switches are used in optical telecommunication systems to route optical signals through networks. As optical telecommunications systems have become more popular, the quantity of data carried through the networks has increased, putting greater capacity demands on the switches. It is known to use wavelength division multiplexed (WDM) signals to enable each optical fibre in the network to carry multiple data channels, those data channels separated by unique central frequencies and having non-overlapping bandwidths. Wavelength selective switches (WSSs) are used to route WDM signals through the network.

Figure 1(a) illustrates schematically a known MxN WSS 100. The MxN switch comprises N input ports 101 and M output ports 102. Each port carries multiple data channels. A bank of 1xM WSSs 103 splits the multiplexed signal from each input port into its separate frequency channels. The demultiplexed data channels are then directed to the M output ports. A bank of Nx1 WSSs 104 at the output combines the data channels into a set of multiplexed signals for output via the output ports 102. In this way, the MxN switch is able to redirect any data channel from an input port to any data channel in an output port, subject to the condition that two channels with overlapping frequencies are not routed to the same output port.

Figure 1(b) illustrates schematically a known switch referred to as an add-drop WSS 200. Add-drop WSS 200 is a special type of WSS in which N input ports 201 are connected to K output ports 202, where K>N. A bank of 1xK WSSs 203 splits the multiplexed signal from each input port into its separate frequency channels. The demultiplexed data channels are then directed to K space switches 204. Each space switch 204 can accept data from any of the 1xK WSSs but can only output data from one of the input ports at a time. The output of each space switch 204 is then output from an output port 202, otherwise known as a drop port. Space switches are simpler to implement than Nx1 switches, and hence the add-drop WSS of figure 1(b) is preferable to the MxN WSS of figure 1(a). This is particularly the case when K is much bigger than N, and the data density in the K output ports is much lower than in the N input ports.

Both the WSSs of figures 1(a) and 1(b) are reversible. For example, edge reconfigurable optical add-drop multiplexers (ROADM) are used for transferring optical data between core dense wavelength divisional multiplexing (DWDM) and more coarse wavelength division multiplexing (CWDM). An add-drop WSS of the type in figure 1(b) is used in the “dropping” direction (from N input ports to K drop output ports) shown in figure 1(b) to transfer from DWDM to CWDM, and in the reverse “adding” direction (from K drop input ports to N output ports) to transfer from CWDM to DWDM.

Figure 2 illustrates switch 300 which takes the form of twin system in a single package formed from two of the NxM add-drop WSSs 200 seen in figure 1(b).. The two WSSs in the switch 300 are independent of each other. The components of the WSS 200 are duplicated in the twin system 300. The switch 300 therefore comprises 2 x N input ports and 2 x M add/drop output ports. The switch 300 also comprises 2 x N 1xM WSSs and 2 x M space switches.

As shown in figure 3 the twin system 300 may be converted to an N degree ROADM 400 by adding connections 401 seen in figure 3. The ROADM 400 comprises N input ports, M drop ports, M add ports and N output ports. The switch 300 also comprises 2 x N 1x(M+N) WSSs and 2 x (M+N) space switches. As illustrated, one WSS operates in a “forward” direction transferring optical signals from N input ports to M drop ports. The other WSS operates in a “backward” direction transferring optical signals from M add ports to N output ports. Connections 401 act as a transit section to transfer signals from N drop ports to N add ports. Specifically, connections 401 act as an NxN switch. Therefore, together, the two WSSs operate so as to transfer optical signals from the N input ports to the N output ports via the transit section formed of N connections. A transit section comprises optics that allow light to pass between the MxN WSSs such that the functionality of one WSS is partly available to the other. The transit allows light to switch between the N inputs of one WSS and N outputs of the other. It does not allow direct switching from the M add to M drop ports.

In passing from the N input ports to the N output ports, signals pass entirely through both WSSs (whereas signals passing to the M drop ports or from the M add ports pass through only one of the WSSs). This path from the N input ports to the N output ports therefore introduces high optical loss due to the number of times the signals pass through components of the WSSs and the fact that additional optical fibres are used.

It would be desirable to develop an improved system to allow internal transit with few additional components and lower loss for transit light.

SUMMARY OF THE INVENTION

According to one aspect, there is provided an optical switch comprising a plurality of independently controllable systems, each system comprising: a set of input ports, each input port configured to transport an optical signal having at least one component frequency channel; a set of output ports corresponding to the set of input ports, each output port configured to transport an optical signal having at least one component frequency channel; a first programmable deflection plane configured to deflect beams incident thereon to form a corresponding first deflected array of beams; a second programmable deflection plane configured to deflect beams incident thereon to form a corresponding second deflected array of beams; and a beam steering optical element group configured to transfer the first deflected array of beams between the first programmable deflection plane and the second programmable deflection plane, the beam steering optical element group of each of the plurality of systems comprising a common plane; wherein the optical switch is configured to form a Fourier conjugate image for the first programmable deflection plane of each of the plurality of systems on the common plane for the plurality of systems, wherein the Fourier conjugate image from the first programmable deflection plane of one system overlaps the Fourier conjugate image from the first programmable deflection plane of at least one other system.

The Fourier conjugate image from the one system may be spatially coincident with the Fourier conjugate image from the at least one other system.

The Fourier conjugate image from the one system may be different to the Fourier conjugate image from the at least one other system.

The respective Fourier conjugate image for a respective system may be formed at the common plane in a steering direction of the respective beam steering optical element group. Herein, the dispersion direction is defined in the plane that the grating demultiplexer spreads the light out. The steering direction is orthogonal to this (defined in the plane that the programmable deflection plane deflects or ”steers” the light).

The beam steering optical element group may comprise a split aperture mirror. The common plane may be located at the split aperture mirror. A split aperture mirror is a mirror configured to allow one (or more) beams to pass through an aperture in the mirror and reflects light not passing the original beam direction (in the steering direction). The split aperture mirror may comprise two or more mirrors. The split aperture mirror may comprise two mirrors separated by a gap. Other exemplary implementations are described herein.

The split aperture mirror may be in a conjugate plane for the first programmable deflection plane.

The beam steering optical element group may comprise a grating arrangement. The common plane may be located at the grating arrangement.

The grating arrangement may be a component of a multiplexer or demultiplexer of the beam steering optical element group.

The grating arrangement may be in a conjugate plane for the first programmable deflection plane.

The beam steering optical element group may comprise one or more 4F arrangements of optical lenses.

The beam steering optical element group may comprise a Faraday rotator and/or a polarising beamsplitter.

The first programmable deflection plane of the one system may be optically connected to the first programmable deflection plane of the at least one other system of the plurality of systems. The optical switch may be configured such that one or more beams of the first deflected array of beams for the one system propagate to the common plane.

The optical switch may comprise a transit optical element group configured to direct the one or more beams of the first deflected array of beams from the common plane to the first programmable deflection plane of the at least one other system.

The beam steering optical element group of a respective system may be configured to: transfer one or more of the first deflected array of beams of the respective system from the first programmable deflection plane of the respective system to the transit optical element group; and transfer one or more of the first deflected array of beams of another system from the transit optical element group to the first programmable deflection plane of the respective system.

The transit optical element group may comprise one or more steering lenses, one or more dispersion lenses and one or more reflectors.

The transit optical element group may comprise one or more of a wedge reflector and a wedge prism.

The grating arrangement may comprise one or more mirrors configured to direct one or more beams from the first programmable deflection plane to the transit optical element group.

The split aperture mirror may comprise a transit mirror configured to direct one or more beams of the first set of deflected beams from the first programmable deflection plane to the transit optical element group.

Each beam steering optical element group may comprise a remapping optical device comprising *n* sets of: a first pair of mirrors configured to provide an optical path for a first set of beams of the first deflected array of beams; and a second pair of mirrors configured to provide an optical path for a second set of beams of the first deflected array of beams, the first and second pairs of mirrors having differently angled surfaces so as to alter the conform arrangement of the first and second sets of beams of the first deflected array of beams to form a remapped array of beams, where *n* is the number of systems in the plurality of systems.

The first pair of mirrors may comprise a first mirror and a second mirror. The second pair of mirrors may comprise a third mirror and a fourth mirror.

The first mirror and the third mirror may be arranged linearly in the steering direction of the respective beam steering optical element group.

The first mirror and the third mirror may be positioned adjacent to each other such that no gap exists between them.

The first mirror and the third mirror may be part of a first set of mirrors in a first mirror plane of the remapping optical device. The second mirror and the fourth mirror may be part of a second set of mirrors in a second mirror plane of the remapping optical device.

The first mirror plane and the second mirror plane may be linearly aligned for all systems of the optical switch.

The mirrors of the second set of mirrors may be positioned in a grid. There may be a gap between each mirror in the grid.

The beam steering optical element group may comprise one or more of a split aperture mirror, a remapping optical device, a grating arrangement of a multiplexer/demultiplexer and one or more other optical systems (which may comprise 4F lens arrangements and steering optical components).

One or more of the first controllable deflection plane and the second controllable deflection plane may be a spatial light modulator, the spatial light modulator being a liquid crystal on silicon display, a liquid crystal panel, a controllable micro-electro-mechanical systems mirrors or a digital light processing device.

The set of output ports may be configured to receive data only from the corresponding set of input ports. The optical switch may be an MxN optical switch. system may be a wavelength selective switch (WSS). The optical switch may be a reconfigurable optical add-drop multiplexer (ROADM) optical switch.

The optical system may comprise a spectral plane which is a Fourier conjugate plane in the steering direction of the second deflection plane and an image plane in the steering direction of the first deflection plane.

The common plane, the spectral plane and the second deflection plane may all be in an image plane of the first programmable deflection plane in the dispersion direction.

The optical system may comprise an optical element configured to generate a gap between the beams incident on it in the dispersion direction is located at the spectral plane.

BRIEF DESCRIPTION OF THE FIGURES

The present invention will now be described by way of example with reference to the accompanying drawings. In the drawings:

Figure 1(a) illustrates a known MxN WSS;

Figure 1(b) illustrates a known add-drop WSS;

Figure 2 illustrates a known twin system formed of two add-drop WSSs;

Figure 3 illustrates a known ROADM switch;

Figure 4 shows a ROADM switch;

Figure 5(a) illustrates a ROADM switch;

Figure 5(b) illustrates two examples of remapping optical devices;

Figure 5(c) illustrates two space switch positions focused on the second programmable deflection plane either both to the side or one either side of the spectra;

Figure 6(a) illustrates a remapping gap optic;

Figure 6(b) illustrates an arrangement of a remapping gap optic and flat mirrors;

Figure 7 illustrates an example of a split aperture mirror;

Figure 8 illustrates another example of a remapping gap optic;

Figure 9(a) illustrates the optical elements included in a twin system looking down on the dispersion direction;

Figure 9(b) illustrates the optical elements included in a twin system looking down on the steering direction;

Figure 9(c) illustrates the spatial layout of the twin system looking down on the dispersion direction;

Figure 10 illustrates the spatial layout of another twin system looking down on the dispersion direction;

Figure 11 illustrates a further ROADM switch utilising NxN transit optics at the split aperture mirror;

Figure 12(a) illustrates the spatial layout of the ROADM switch looking down on the dispersion direction;

Figure 12(b) illustrates a split aperture mirror;

Figure 13(a) shows an optical arrangement using four-element transit optics from the split aperture mirror in the steering axis;

Figure 13(b) shows a split aperture mirror;

Figure 13(c) shows a further optical arrangement using four-element transit optics from the split aperture mirror in the steering axis;

Figure 14(a) shows the operation of the transit ports with respect to the rest of the system of Figure 13(a) in the dispersion direction.

Figure 14(b) shows the system of Figure 14(a) in the steering direction;

Figure 15(a) shows a layout of a split aperture mirror transit utilising a six-element transit system;

Figure 15(b) shows an example of a split aperture mirror design for the case where four ports are chosen for transit;

Figure 16(a) shows further detail of the six-element transit optics in the steering direction;

Figure 16(b) shows a wedge prism optical element of a transit optical element group;

Figure 17(a) shows the operation of the transit ports of the system of Figure 16(a) with respect to the rest of the system in the dispersion direction;

Figure 17(b) shows the operation of the system of Figure 17(a) from the steering direction;

Figure 18 shows a further ROADM switch utilising NxN transit optics at the grating multiplexer;

Figure 19(a) shows the layout of an optical switch with a four-element transit optical system emergent from a grating using a single sample mirror;

Figure 19(b) shows a single sample mirror;

Figure 19(c) shows a layout diagram for the arrangement of Figure 19(a) in the dispersion direction;

Figure 19(d) shows a layout diagram for the arrangement of Figure 19(a) in the steering direction;

Figure 20(a) shows the layout of an optical switch with a six-element transit optical system emergent from a grating using a sample mirror;

Figure 20(b) shows a sample mirror suitable for use with the switch of Figure 20(a);

Figure 20(c) shows a layout diagram for the arrangement of Figure 20(a) in the dispersion direction;

Figure 20(d) shows a layout diagram for the arrangement of Figure 20(a) in the steering direction;

Figure 21(a) shows the layout of an optical switch with a four-element transit optical system whereby the transit optics are linked to the grating through a gap optic arrangement with a flat mirror;

Figure 21(b) shows a gap optic suitable for use with the switch of Figure 21(a);

Figure 21(c) shows further detail of the transit optics of the arrangement of Figure 21(a) in the steering direction;

Figure 22 shows a ROADM switch with a direct connection between the input and output transit ports without any switching;

Figure 23(a) shows the layout of an optical switch with a non-switched transit at the split aperture plane;

Figure 23(b) shows a split aperture mirror suitable for use with the switch of Figure 23(a);

Figure 23(c) shows a layout diagram for the arrangement of Figure 23(a) in the dispersion direction;

Figure 23(d) shows a layout diagram for the arrangement of Figure 23(a) in the steering direction;

Figure 24(a) shows the layout of an optical switch where transit optics are enacted for light passing from the first programmable deflection plane before reaching the diffraction grating;

Figure 24(b) shows grating with a transit mirror suitable for use with the switch of Figure 24(a);

Figure 24(c) shows a layout diagram for the arrangement of Figure 24(a) in the dispersion direction;

Figure 24(d) shows a layout diagram for the arrangement of Figure 24(a) in the steering direction;

Figure 25(a) shows the layout of an optical switch with a four-element transit optical system whereby the transit optics are linked to the grating through a gap optic arrangement with a flat mirror;

Figure 25(b) shows a gap optic suitable for use with the switch of Figure 25(a);

Figure 215c) shows a layout diagram for the arrangement of Figure 25(a) in the dispersion direction;

Figure 25(d) shows a layout diagram for the arrangement of Figure 25(a) in the steering direction;

Figure 26 shows an optical arrangement for an optical switch comprising a polarising beamsplitter and a Faraday rotator.

Figure 27 shows a further optical arrangement comprising a polarising beamsplitter and a Faraday rotator.

Figure 28 shows a further optical arrangement comprising a polarising beamsplitter and a Faraday rotator.

DETAILED DESCRIPTION

The following describes several exemplary optical switches which utilise two or more programmable deflection planes and a beam steering optical element group, which can include components such as a split aperture mirror (SAM) and a gap optic device, to optically route light from a set of input ports to a set of output ports. The described optical switches may be wavelength selective switches (WSSs). These WSSs may be implemented as add-drop WSSs (adWSS), for example for transferring light from core DWDM networks to lower capacity CWDM networks. Alternatively, the described WSSs may be implemented as MxN WSSs or MxN two-plane space switches. All the examples described herein use optical components to route the light through the switches. There is no absorption and re-emission of light.

Fourier optics is a well-known field of optics using the property that a lens has such that in two planes either side of a lens one focal length away are Fourier conjugate planes, meaning that one plane (for small angles) is a Fourier transform of the other with angle from the plane normal and position in the plane as conjugate variables, i.e. the spatial distribution of the light in one plane is proportional to the angular distribution in the other and vice versa. Two such systems in a line is referred to as a “4F” system, as the length is four focal lengths. This system does two Fourier transforms forming an image of the initial plane inverted in space and angle. A Fourier conjugate plane is formed where there are an odd number of such lenses separated in this way and an image plane (inverted or non-inverted) where there are an even number of such lenses. These planes can be referred to as a Fourier conjugate plane and an image conjugate plane respectively.

In the optical switches described herein, the dispersion and steering directions are both orthogonal to each other and to the optical axis. The dispersion direction is defined in the plane that the grating demultiplexer spreads the light out. The steering direction is orthogonal to this (defined in the plane that the programmable deflection plane deflects or ”steers” the light).

Figure 4 shows an example of how the loss over the system 500 can be reduced relative to the system of Figure 3. In this case the N input and N output transit ports are directly connected, as shown at 501, through specific switching positions without needing to pass through the space switch deflection planes. Thus the transit section only passes through two deflection planes and has a shorter optical path, resulting in a much lower loss. The ROADM configuration using the twin add/drop WSS described herein can use an internal transit to enable this. The approach can also be used for other MxN WSS or add/drop WSS systems.

Figures 5(a), 5(b) and 5(c) illustrate an exemplary embodiment of an optical switch. In this example, the optical switch is a multiple MxN WSS or add/drop WSS, where multiple independent WSSs exist in the same package. Each WSS may have programmable deflection planes, which in this example are spatial light modulators (SLMs) that have their normal pointing in the same hemisphere, or share the same SLM for all switching planes. The WSSs are independently controllable systems. It is not possible to switch light between the input and output ports of different WSSs. The following description will refer to a twin add/drop WSS, but in other implementations there may be multiple systems or full MxN or space switch only (with no demultiplexing).

Figure 5(a) shows an example of a twin NxM system. The twin system comprises two sets of N independent input ports 601 (601a, 601b) and two sets of M independent output ports 602 (602a, 602b). Adjacent to the N input ports 601a, 601b the system includes a fan lens 603. The system further includes a split aperture mirror 604, which is described in more detail below. The system also includes an optical system 605. In this example, the optical system 605 comprises a 4F imaging system which acts in the dispersion direction. The optical system 605 forms an image conjugate plane in the dispersion direction with an optional demultiplexer/multiplexer at the central plane, and a Fourier conjugate plane in the steering direction between the split aperture mirror 604 and the first programmable deflection plane 606. The optical system 605 comprises two lenses having optical power in the dispersion direction and a demultiplexer located between the two lenses having optical power in the dispersion direction. The demultiplexer is located at the Fourier plane between the two lenses. The optical system 605 further includes at least one lens with optical power in the steering direction located between the two lenses which have optical power in the dispersion direction. In this system, the steering direction is orthogonal to the dispersion direction. The lens may be a lens in a Fourier configuration. The optical system 605 may generally comprise three lenses or any odd number of lenses having optical power in the steering direction.

The two sets of N independent input ports 601a, 601b are converged together to a single location by fan lens 603 through the aperture in a mirror 604 (which in this example is a split aperture mirror) and are propagated by an optical system 605 to a first programmable deflection plane 606. The first programmable deflection plane 606 may take the form of a spatial light modulator (SLM) plane. The SLM plane is typically implemented by a liquid crystal on silicon (LCoS) device or optical microelectromechanical system (MEMS). LCoS devices apply a holographic beam deflection to the spectrum of channels incident on it.

The optical system 605 comprises a 4F image system in one direction (the dispersion direction) and a Fourier conjugate plane in a second orthogonal direction (the steering direction). In the central Fourier plane of the dispersion lenses is placed a grating or grism (grating and prism) assembly that splits the incident light into its separate frequency channels onto the first programmable deflection plane 606. The addition of a prism can improve the linearity of the channel widths incident on the first programmable deflection plane from the grating.

In this example, for a twin system, there are 2N spectra on the first programmable deflection planes 606, N for each respective first programmable deflection plane for each respective WSS system. The plane 606 then directs each individual channel in each spectra corresponding to the output port location in the corresponding WSS system. The deflection is in the steering direction and the grism/grating disperses in the dispersion direction. The deflected beams form one single set of images on the split aperture mirror 604 separate from the fan in location (i.e. the location at which the fan lens directs the beams from the input ports). The deflected beams in the steering directions are focussed in the Fourier conjugate plane by the steering optics of optical system 605 at different locations away from the fan-in point. They are thus directed to the next optical system 607.

The images at this plane are overlapping. The images at this plane may be combined into a single array and coincident. Here, coincident does not mean that the actual images are the same, only that possible switch locations on the space switch plane are at the same place.

At this point, in the embodiment of Figure 5(a), the split aperture mirror 604 directs these image beams to propagate through another 4F dispersion and conjugate steering optical system 607 to a remapping gap optic (RGO) 608, which will be described in further detail below.

Optical system 607 comprises a 4F imaging system. The optical system 607 comprises two lenses which have optical power in the dispersion direction. The optical system 607 further includes at least one lens having optical power in the steering direction located between the two lenses having optical power in the dispersion direction. The lens having optical power in the steering direction may be a lens in a Fourier configuration. As described above, optical system 607 forms an image conjugate plane in the dispersion direction and a Fourier conjugate plane in the steering direction. As the light has been re-multiplexed by the pass back through the grating in optical system 605, the data here is fully multiplexed. The light incident on the RGO 608 will have passed through two lenses configured in the Fourier configuration in the steering direction and this will form an inverted image conjugate plane of the spectra on the first programmable deflection plane(s) 606.

The multiplexed image of the 2N spectra at the RGO plane is then split using a mirror array according to which spectra are associated with the WSS to form two columns of spectra separated in the dispersion direction that are also changed to introduce a gap in the columns in the steering direction.

As mentioned above, the optical structure 608 may be known as an RGO. The RGO 608 is an optical structure configured to alter the configuration of the beams incident on it and also to generate a gap between those beams. The optical structure 608 may comprise a mirror array positioned such that light beams incident on it from optical system 607 are split into a first set of beams and a second set of beams, where the first and second sets of beams exit the structure as two distinct spatially separated groups of beams. In other words, the optical structure 608 splits the incoming light into two portions of light separated by a gap. The first and second sets of beams output from the optical structure 608 are thus parallel and separated from each other by a gap.

The light is propagated through another optical system 609 to a second programmable deflection plane 610, an image of the two columns of output ports. The second plane 610 deflects the beams through the optical system 609 to the gaps in RGO 608 and then to the two columns of output ports 602a, 602b through a fan lens 611.

The system 600 further includes optical system 609. Optical system 609 may take the same form as optical system 605 previously described, except for the inclusion of a demultiplexer. For example, optical system 609 may comprise a set of two lenses having optical power in the dispersion direction and at least one lens having optical power in the steering direction positioned between the two lenses having optical power in the dispersion direction. According to another example, optical system 609 may also include a demultiplexer.

The second programmable deflection plane 610 may take the same form as the first programmable deflection plane 606. As previously described, the first and second programmable deflection planes 606, 610 may be located on separate SLM devices or may be located on a single common SLM device. Finally, the system includes another fan lens 611.

The path of light beams input from the N input ports 601a, 601b is generally as follows. Input light beams from N input ports 601a pass through fan lens 603, SAM 604 and optical system 605 before being incident on the first programmable deflection plane 606. The input light beams then pass through the optical system 605 towards the first programmable deflection plane 606. Light beams input from the N input ports 601b take an equivalent path through fan lens 603, SAM 604 and optical system 605 before being incident on a first programmable deflection plane 606.

The optical systems 603-611 may be common to both WSSs, ie. the same physical elements. Thus there can advantageously be very few additional components when moving from a single adWSS to a twin (or multiple) adWSS of this design.

The optical system 605 images the optical signal in the dispersion plane using the two lenses which have optical power in the dispersion direction. The demultiplexer in the optical system 605 spreads and collimates the incoming light in the dispersion plane onto the first programmable deflection plane 606. The incoming light therefore forms spectra on the first programmable deflection plane(s) 606.

The lens having optical power in the steering direction of optical system 605 may be in a Fourier configuration with the first programmable deflection plane 606 and the remapping optical device 604 such that the optical system 605 forms a Fourier conjugate in a direction normal to the beam path, along the steering axis. In other words, the optical system 605 also creates a conjugate Fourier plane in the steering direction. The demultiplexed light incident on the first programmable deflection plane 606 is deflected in the steering direction and passed back through the corresponding optical system 605 to the SAM 604. Since the demultiplexed light passes back through optical system 605 in the opposite direction, the demultiplexer acts as a multiplexer in the reverse direction. The demultiplexed light incident on the optical system 605 is therefore recombined as it passes back through the optical system. Due to the angular deflection imparted on the light by the first programmable deflection plane 606, once the light has been deflected by the programmable deflection plane 606 and has passed back through optical system 605, as will be explained in more detail below, the deflected multiplexed light is intercepted by the SAM 604 such that the light is deflected in a direction away from input ports 601.

In this case the “top” and “bottom” deflected beams (origination from input ports 601a and 601b respectively) from the corresponding parts of the spectra on the first programmable deflection plane 606 can be remapped from top and bottom to side by side in two different ways by the remapping optical device 608, as shown in figure 5(b).

As previously explained, there are two sets of input signals to the twin system 600 via the two sets of N input ports 601a, 601b. Light incident from the input ports 601a, 601b passes through a fan lens 603 to the same spot. Both sets of input signals are incident on the first programmable deflection plane 606. Specifically, the two sets of input signals are incident on two different portions of the plane 606 and then pass back through the optical system 605 towards the SAM 604. At the SAM 604, the sets of beams are passed to optical system 607 at then to the remapping optical device 608, also referred to as the remapping gap optic (RGO).

Figure 5(b) illustrates an example of a remapping optical device 608. The remapping optical device 608 includes a first mirror array 701 at a first mirror plane and a second mirror array 702 at a second mirror plane. The first mirror array 701 comprises four mirrors 701a, 701b, 701c and 701d. Mirrors 701a, 701b, 701c and 701d of the first mirror array 701 are arranged in a single column. In this example, there are no gaps between the mirrors 701a, 701b, 701c, 701d. However, in other implementations there can be a gap between any of the mirrors. The second mirror array 702 comprises four mirrors 702a, 702b, 702c and 702d. Mirrors 702a, 702b, 702c and 702d of the second mirror array 702 are arranged in a 2x2 grid. There are gaps between the mirrors 702a and 702b, and between 702c and 702d. These gaps allow a beam to transit through between the mirrors.

Figure 5(b) illustrates a first set of incoming beams 705 and a second set of incoming beams 706. The first set of incoming beams 705 are those which originated from input ports 601a (the “top” input ports) and are incident on the remapping optical device 608 from optical system 607. The second set of incoming beams 706 are those which originated from input ports 601b (the “bottom” input ports) and are incident on the remapping optical device from optical system 607. The first programmable deflection plane 606 deflects the beams incident on it so that their Fourier conjugate image is back at a common plane of the SAM 604. In the NxM optical switch, the Fourier conjugate image from the first programmable deflection plane of one of the WSSs of the twin system overlaps the Fourier conjugate image from the first programmable deflection plane of the other WSS of the twin device.

Figure 5(b) shows that beams 705 which are incident on mirror 701a of the first mirror array are directed to mirror 702a of the second mirror array. Beams 705 which are incident on mirror 701b of the first mirror array are directed to mirror 702b of the second mirror array. The pair of mirrors 701a, 702a therefore provide an optical path for a subset of beams 705 and the pair of mirrors 701b, 702b provide an optical path for a different subset of beams 705. Beams 706 which are incident on mirror 701c of the first mirror array are directed to mirror 702c of the second mirror array. Beams 706 which are incident on mirror 701d of the first mirror array are directed to mirror 702d of the second mirror array. The pair of mirrors 701c, 702c therefore provide an optical path for a subset of beams 706 and the pair of mirrors 701d, 702d provide an optical path for a different subset of beams 706. Each mirror in in a pair may be parallel with respect to the other mirror in the pair. The result of incoming light being incident on pairs of parallel mirror surfaces is that the direction of light entering the beam steering device is the same direction as the light leaving the device and no rotation of the optical image about the optical axis. There is therefore no need for additional optical components in the system to later correct for such rotation. Furthermore, the path length for each chief ray for each port from one plane normal to the optical axis before the first mirror plane to after the second mirror plane is the same for all rays.

Thus, each subset of beams follows a different path through the mirror arrays 701, 702 thereby causing the geometrical distribution of the groups of the beams to change. The single column of incoming light beams are thus remapped to two columns (i.e. a 2 dimensional array) of light beams. In other words, the four mirrors of the first mirror array 701 positioned above and below each gap deflect the light onto the four mirrors in a 2x2 arrangement of the second mirror array 702 so that light from each group of N input beams corresponds to a column in the plane of the second mirror array.

In the optical device 800, the first mirror array comprises mirrors 801a, 801b, 801c, 801d. The second mirror array comprises mirrors 802a, 802b, 802c, 802d. In device 800, beams 705 forming a column incident on the first mirror array 801 are mapped to a row at the second mirror array. Beams 706 forming a column incident on the first mirror array 801 are mapped to a row at the second mirror array positioned below the row formed of beams 705. Specifically, beams 705 which are incident on mirror 801a of the first mirror array are directed to mirror 802a of the second mirror array. Beams 705 which are incident on mirror 801b of the first mirror array are directed to mirror 802c of the second mirror array. Beams 706 which are incident on mirror 801c of the first mirror array are directed to mirror 802d of the second mirror array. Beams 706 which are incident on mirror 801d of the first mirror array are directed to mirror 802b of the second mirror array.

The two space switch positions can then be focused on the second programmable deflection plane 610 either both to the side or one either side of the spectra, as shown in Figure 5(c). The column of space switches can be two separate columns of M space switches, as shown in Figure 5(c). Other possible remapping arrangements are possible. Also, the two planes can exist over two or more SLMs.

The main advantage of this approach is that the number of components is significantly reduced and only a single custom optic (the RGO) is needed. It also means that nearly the whole system uses the same optics as in a single NxM WSS system, with a similar layout and optical height.

The subsequent embodiments will describe this twin optical switch in more detail and illustrate methods by which the twin system utilising an RGO can be converted into a ROADM with a description of possible transit optics for a link between the two WSS systems.

Herein, a transit optical element group comprises multiple optical components that allow light to pass between the independently controllable MxN WSS systems such that the functionality of one WSS is only partly available to another. The embodiments described herein primarily concern add/drop WSSs configured as a ROADM (i.e. one forward (to drop) and one reverse (from add ports)). The transit optical element group allows light to switch between the N inputs of one WSS and N outputs of another. It does not allow direct switching from the M add to M drop ports. This specific configuration is valuable because it can be used to drop or add a small number of channels from a dense data stream, most of which passes through ("transits"). This approach can however be extended to two-switch-plane WSSs, such as full demultiplexed MxN (see figure 1(a)) and space switch WSSs.
As schematically illustrated in Figure 6(a), in a gap optic device, imaged ports on the first mirror plane 660 are directed in order to create a gap in the spectral plane so that light from the second programmable deflection plane 610 through optical system 609 can be deflected through the gap to the output ports 602a, 602b. In some embodiments, a third plane mirror (and optionally further mirrors) can be used at the input and/or output to the RGO to direct the output light in an appropriate direction.

Figure 6(a) illustrates a remapping optical device 608, referred to as a RGO, which may be used in the embodiment of figure 5(a), and also in Figures 11 and 18 below. It shows the remapping of two sets of four input ports (i.e. N=4) input in a vertical manner towards a side by side arrangement on the second mirror plane 661 including the gap required by the gap optic. As mentioned above, a third mirror (not shown) can be used to redirect the output beam.

The first mirror plane of the RGO is shown at 660. The second mirror plane of the RGO is shown at 661. The remapping optical device 608 includes a first mirror array 701 at the first mirror plane 660 and a second mirror array 702 at the second mirror plane 661. The first mirror array 701 comprises four mirrors 701a, 701b, 701c and 701d. Mirrors 701a, 701b, 701c and 701d of the first mirror array 701 are arranged in a single column. In this example, there are no gaps between mirrors 701a, 701b, 701c and 701d. However, in other implementations there may be gaps between any of the mirrors. The second mirror array comprises four mirrors 702a, 702b, 702c and 702d. Mirrors 702a, 702b, 702c and 702d of the second mirror array 702 are arranged in a 2x2 grid. There is a gap between each of the mirrors of the second array 702.

As previously explained, there are two sets of input signals to the twin system 600 via the two sets of N input ports 601a, 601b. Light incident from the input ports 601a, 601b passes through a fan lens 603, SAM 604 and the optical system 605 before reaching the first programmable deflection plane 606 as previously described.

Also explained above, both sets of input signals are incident on the first programmable deflection plane 606. Figure 6(a) illustrates a first set of incoming beams 705 and a second set of incoming beams 706 to the RGO 608. These beams have previously passed through optical system 607. In the configuration of RGO 608 in Figure 5(b), the first set of incoming beams 705 are those which originated from input ports 601a (the “top” input ports) and are incident on the remapping optical device from optical system 607. The second set of incoming beams 706 are those which originated from input ports 601b (the “bottom” input ports) and are incident on the remapping optical device from optical system 607. The following description assumes the configuration of the RGO 608 shown in Figure 5(b), though the configuration of the RGO 800 shown in Figure 5(b) is also possible.

Figure 6(a) shows that beams 705 which are incident on mirror 701a of the first mirror array are directed to mirror 702a of the second mirror array. Beams 705 which are incident on mirror 701b of the first mirror array are directed to mirror 702b of the second mirror array. The pair of mirrors 701a, 702a therefore provide an optical path for a subset of beams 705 and the pair of mirrors 701b, 702b provide an optical path for a different subset of beams 705. Beams 706 which are incident on mirror 701c of the first mirror array are directed to mirror 702c of the second mirror array. Beams 706 which are incident on mirror 701d of the first mirror array are directed to mirror 702d of the second mirror array. The pair of mirrors 701c, 702c therefore provide an optical path for a subset of beams 706 and the pair of mirrors 701c, 702c provide an optical path for a different subset of beams 706. Each mirror in a pair may be parallel with respect to the other mirror in the pair. Each mirror in a pair may be linearly aligned with respect to the other mirror in the pair. The result of incoming light being incident on pairs of parallel mirror surfaces is that the direction of light entering the beam steering device is the same direction as the light leaving the device and no rotation of the optical image about the optical axis. There is therefore no need for additional optical components in the system to later correct for such rotation. Furthermore, the path length for each chief ray for each port from one plane normal to the optical axis before the first mirror plane to after the second mirror plane is the same for all rays. As a result, there is no optical delay between any of the beams along the optical axis caused by the RGO geometry.

Thus, each subset of beams follows a different path through the mirror arrays 701, 702 thereby causing the geometrical distribution of the groups of the beams to change. The single column of incoming light beams are thus remapped to two columns (i.e. a 2 dimensional array) of light beams. In other words, the four mirrors of the first mirror array 701 positioned deflect the light onto the four mirrors in a 2x2 arrangement of the second mirror array 702 so that light from each group of N input beams corresponds to a column in the plane of the second mirror array.

According to further examples, there may be more than four mirrors in the first and second mirror arrays and more than two columns may be formed at the second mirror plane. Indeed, any particular shape or array can be formed such as hexagonal, circular, triangular as well as square and rectangular when combined with additional known optics.

In some implementations, the divergence of the beams can be controlled. Astigmatic optics can be used to do this. This may move the steering focus away from the mirror gap. The gap may be larger to accommodate this (for example, increased by 50%). For these pairs of mirrors, the propagation length through the system from a plane normal to the optical axis before the first mirror plane 660 to one after the second mirror plane 661 are the same for all chief rays for all of the ports.

Figure 6(b) shows an example of the application of three directing mirrors 651, 652, 653 around the two mirror planes of the RGO 608 as viewed from above (looking down onto the dispersion plane). The directing mirrors 651, 652, 653 are all rotated about parallel axes normal to the optical axis (in this case, an axis in the steering direction). In this case they are also normal to the dispersion plane. This ensures there is no rotation of the images relative to the steering direction.

Figure 7 illustrates a possible split aperture mirror. It illustrates the deflection in the steering axis onto a mirror due to an angular deflection from the first programmable deflection plane 3206 (the steering optics are not shown). The input beams are focussed through the aperture to propagate to the plane 3206. 3301 is one of the input beams. 3203 is the fan lens (603 in Figure 5(a)), 3305 is a component part of SAM 604, 3205 are the dispersion lenses of optical system 605 (without the steering lens system) and 3206 are the first deflection planes 606. The mirror deflection of 3305 is towards optical system 607.

As shown in Figure 7, a SAM is an optical structure to which light 3301 is input. In figure 7, the input light is parallel to the optical axis. This may be known as “on-axis” light. Alternatively the input light may be known as “off-axis” light where the input light is not parallel to the optical axis. The structure to which the light in each case is input includes a fan lens 3203, an optical system 3205 and a programmable deflection plane 3206, as previously described. The optical system 3205, corresponding to the optical system 605 in Figure 5(a), may comprise a set of two 4F lenses configured to image the signal in the dispersion plane and a lens configured to form a Fourier conjugate in the steering direction. Figure 7 illustrates only the set of 4F dispersion lenses. Any components of the optical system 3205 in the steering plane are not shown.

In figure 7, the SAM 3305 is a split aperture mirror. The SAM 3305 comprises two mirrors separated by a gap. In the example shown, the two mirrors are displaced from one another in the steering direction. Figure 7 shows that the input light is focused by the fan lens 3203 so that it passes through the gap between the two mirrors. In other words, the input light passes by the SAM 3305 without being deflected. Once the light has been deflected by the programmable deflection plane 3206 and has passed back through optical system 3205, the deflected light is intercepted by one of the two mirrors of the SAM 3305 at its focus. As mentioned above, the optical system 3205 includes a steering lens (not shown), which may be positioned between the two 4F dispersion lenses. The steering lens forms a Fourier conjugate focus in the steering direction at the SAM mirror plane such that the light is intercepted by one of the two mirrors of the SAM 3305. In other words, the steering lens of the optical system 3205 deflects the light deflected by the programmable deflection plane 3206 in the steering direction so that instead of passing through the gap between the two mirrors, the light is incident on one of the two mirrors forming the SAM 3305. The light is then deflected by the intercepting mirror such that the light is directed away from the input light. Other possible arrangements for the SAM may alternatively be used.

This second mirror plane 661 of the RGO 608 works in reverse to the above, where the two mirrors are the second mirror plane 661 of the RGO 608 with the gap. Light from the mirrors is deflected to the second programmable deflection plane to be deflected through the gap to the fan lens over the output ports. In the twin system, there are two columns of output ports and two mirror columns with gaps. There is however only one of each other element of this system.

Despite the fact that the incident Gaussian beam waist in the steering direction would be large (as N is generally much smaller than M for an NxM optical switch), there is a large divergence of the beam at the RGO 608 due to the fact that there are a large number of ports incident. As the beam waist in the dispersion axis is generally small and thus has a high divergence (this can be mitigated by adding magnification to the optics but there is generally a limit to how much it can be controlled), the beam sizes at the two mirror planes 660, 661 of the RGO 608 can be controlled so there is no crosstalk induced. Minimising the separation of the two mirror planes 660, 661 is possible to minimise the effect of divergence.

Alternatively, an astigmatism can be applied to the input light by the transmission optics from the first programmable deflection plane 606 to the gap optic 608. This may be applied by the optical system 607. This astigmatism focusses the steering plane on the first mirror plane 660 and the dispersion waist on the second mirror plane 661. This is useful in the case shown in Figure 8, where a vertical set of mirrors are separated in the vertical axis. It is important that the beam is in focus in the steering axis, though it is less important in the dispersion axis. In the case where the mirrors are laterally separated on the second mirror plane 661, this separation can minimise coverage on the second programmable deflection plane on the space switch area. Thus the beam on the second plane should preferably be in focus in the dispersion direction. The light then propagates through an optical system that corrects out the astigmatism before reaching the second programmable deflection plane 610. The astigmatism may be corrected by optical system 609. The astigmatism can be affected by altering the position and focal length of the steering optics relative to the dispersion optics in optical system 609. It does not require additional elements. The same can be applied for correcting the astigmatism afterwards.

On return from the second programmable deflection plane 610 (e.g. SLM), the light is astigmatic again, so the focus at the gap will be in the dispersion plane. It is thus preferable to allow extra space in the gap size for an out of focus beam in the steering direction. A modification to the output anamorphic telescope can correct for this astigmatic correction, as well as making the beam circular. The output optics, such as lens 611 or the ports 602, can then remove the astigmatism before coupling to the output fibres.

Figure 9(a) shows an optical layout of an exemplary twin system 900 when viewed in the dispersion direction (i.e. along the steering direction) of the system described by the block diagram of figure 5(a) and utilising the RGO of any of figures 6(a), 6(b) and 8. Elements having the same number as a previously described element are as previously described.

Figure 9(a) shows the elements in the order input light passes through them. The same element may be shown multiple times if there are multiple passes of that element. The twin system 900 of figure 9(a) comprises two sets of N input ports 601a, 601b. When viewed along the steering direction as in figure 9(b), these two sets of ports appear as one column of ports. Each port is coupled to a respective coupling lens 901 and then passes through a polarisation compensation unit 902. As previously described, the input light passes through fan lens 603. After the fan lens 603, the light passes through an anamorphic telescope 903, which is known in the art. This telescope 903 is configured to alter the Gaussian beam waists in orthogonal steering and dispersion axes by different magnifications while focussing both axes to the same place at the SAM 604.

As previously discussed, the input light then passes through a split aperture mirror 604 which is located at space switch plane 904. After passing through the split aperture mirror 604 unaffected, the light is incident on optical system 605. In the example seen in figure 9(a), the optical system 605 is a 4F imaging system with Fourier steering (also forming a Fourier conjugate plane at 606 in the steering direction) and a multiplexer/demultiplexer comprising a grating 907 and an optional prism (not shown).

In this example, the optical system 605 comprises a steering cylindrical mirror 905a, a dispersion cylindrical mirror 906a, a steering cylindrical lens 905b, a grating 907, a steering cylindrical lens 905c and a dispersion cylindrical mirror 906b. The dispersion components have optical power in the dispersion direction and the steering components have optical power in the steering direction.

Light is then incident on the first programmable deflection plane(s) 606 (there is one first programmable deflection plane 606 for each WSS system, so two for a twin system for example) at the spectral plane 908. The spectral plane 908 can also be referred to as the image conjugate plane of the first programmable deflection plane 606. The space switch plane 904 can also be referred to as the image conjugate plane of the second programmable deflection plane 610. Spectra are formed on the first programmable deflection plane. The spectra on the first programmable deflection plane 606 are indicted throughout as 916. 2N spectra are formed in all of the embodiments described herein with 2 sets of N input ports across the two first programmable deflections planes 606 of the twin system.

Light deflected by the first programmable deflection plane 606 is deflected back through optical system 605 towards the split aperture mirror 604.

The beams are then input to optical system 607. In the example shown in figure 9(a), the optical system 607 is a 4F imaging system with Fourier steering also forming a Fourier conjugate plane at RGO 608 in the steering direction. The optical system 607 comprises a dispersion cylindrical lens 909a, a steering cylindrical mirror 910 and a dispersion cylindrical mirror 909b. In other implementations, any odd number of steering lenses in a Fourier configuration may be applied. As above, the dispersion components have optical power in the dispersion direction and the steering components have optical power in the steering direction.

The beams are then incident on the remapping gap optic 608. Light of both sets of beams then passes through optical system 609. In this example, optical system 609 comprises a dispersion cylindrical mirror 911a, a steering cylindrical mirror 912 and a dispersion cylindrical mirror 911b. The light from both sets of beams is then incident on the second programmable deflection plane 610 at the space switch plane 904. In the example shown in figure 9(a), the optical system 609 is a 4F imaging system with Fourier steering, with a Fourier conjugate image being formed in the steering direction. The light is deflected back through optical system 609 towards the remapping gap optic 608.

At the remapping gap optic 608, beams 705 and 706 pass through the respective gaps created in the incident beams by the gap optics and continue on towards the output ports 602a, 602b which are also positioned side-by-side along the dispersion direction. Before reaching the output ports 602a, 602b, the beams pass through another anamorphic telescope 913, a polarisation compensation unit 914 (which can be used if directionless operation is desired) and coupling lenses 915. The anamorphic telescope 913 is configured so as to make the

Gaussian waist the same for the dispersion and steering directions and remove any astigmatism, if this has been applied.

Applying an astigmatic correction can be achieved by altering the focal lengths of the 4F arrangement of dispersion cylindrical lenses 909a and 909b so that they are more than half the focal length of steering cylindrical mirror 910. The focus of the latter mirror is on the first RGO mirror plane and the 4F dispersion lenses on the second RGO mirror plane. This can be removed by making the same change in the opposite direction in dispersion cylindrical mirrors 911a and 911b with steering cylindrical mirror 912, and in the output anamorphic telescope arrangement 914.

Figure 9(b) illustrates the same twin system 900 looking down on the steering direction (i.e. along the dispersion direction). Figure 9(b) therefore shows the system in an orthogonal direction to figure 9(a). The components seen in figure 9(a) are therefore also seen in figure 9(b). For example, figure 9(b) shows that light from input ports 601a is focused through fan lens 603 to a circular focus 1001a and is subsequently focused to an anamorphic focus 1002a such that it passes through the split aperture mirror 604. Light from input ports 601b is focused through fan lens 60 to a circular focus 1001a and is subsequently focused to an anamorphic focus 1002a such it passes through the split aperture mirror 604.

Steering cylindrical lens 910 in this arrangement forms a Fourier conjugate image in the steering direction of the first mirror plane of the split aperture mirror plane, which is the same as an inverted image conjugate plane of the first programmable deflection plane(s). Steering cylindrical lens 912 makes a Fourier conjugate image on the second programmable deflection plane 610 and the ratio between steering cylindrical lens 912 and 910 gives the required magnification in the steering direction from the split aperture mirror 604 to the second programmable deflection plane 610.

Furthermore, figure 9(b) illustrates that when both sets of beams are incident on the mirror planes 660, 661 of the RGO (which are positioned side-by-side in the dispersion direction), a gap is created between the incoming beams. Figure 9(b) illustrates that after both sets of beams have been deflected by the second programmable deflection plane 610, they pass through optical system 609 and pass through the created gap in the RGO 608 on the way to the output ports 602a, 602b.

Figure 9(c) shows an exemplary layout of the optics of a twin NxM (in this diagram a twin 4x16, for example) that satisfies the block diagram of Figure 5(a) and illustrated in Figures 9(a) and 9(b) utilising the RGO of figures 6(a), 6(b) or 8.

The spatial layout of the twin system in Figure 9(c) is shown looking down on the dispersion direction (i.e. along the steering direction) and includes the same elements as those described with respect to figures 9(a) and 9(b). Figure 9(c) shows that the system further includes a number of flat redirecting mirrors 1100, 1101, 1102, 1103, 1104 and 1105 to direct the input beams between the various optical components in the system. In the example seen in figure 9(c) (and in subsequent embodiments), the first programmable deflection plane 606 is formed on the same SLM device as the second programmable deflection plane 610 and is flat in the x,y plane. Two opposing 45° mirrors can allow access to the deflection plane surface.

The two sets of N input ports are treated as a single 2N set of input ports in a single NxM design to the first programmable deflection plane 606 and then to the split aperture mirror 604. The 2N sets of ports transfer through two dispersion 4F lenses with a multiplexer grating and optional prism at the 4F central plane. The optical system 605 also has a three-element steering lens arrangement in order to form a conjugate plane of the first programmable deflection plane both at the grating plane and at the SAM. For this arrangement, steering cylindrical lens 905c has the same focal length and position as dispersion cylindrical mirror 906b and can be a single circularly symmetric optic with equal power in the steering and dispersion directions.

As mentioned above, this optical system 605 forms a column of 2N spectra on the first programmable deflection plane 606. The deflected light passes back through this system to the split aperture mirror 604 forming a single integrated column of port selections on the split aperture mirror 604 to be deflected to the RGO 608 via a dispersion cylindrical 4F lens and mirror (909a and 909b) that focus the light on the second mirror plane of the gap optic. Dispersion cylindrical lens 909a and flat mirror 1103 is the optimal arrangement for minimum aberration, but they can be a single mirror element. In some implementations, 909a, 909b and 910 can be lenses in a single path from 604 to 608, with shorter focal lengths for example. Other layouts are also possible.

If an astigmatism is not applied, a cylindrical lens with power in the steering axis (steering cylindrical lens 910) can be positioned to be equidistant from (equal to the lens focal length) the SAM 604 and the first 660 or second 661 plane of the RGO mirrors and be at the centre plane of component 909a and 909b and the dispersion focus is the same as that of the steering focus. Light from the RGO to the second programmable deflection plane 610 then passes through dispersion axis cylindrical 4F components 911a and 911b to image the chosen focus plane to the second programmable deflection plane 610. A steering axis cylindrical lens 912 is then positioned to create a Fourier conjugate plane of the first mirror plane of the RGO to the second programmable deflection plane 610. Steering mirror 912 is in the central plane of mirrors 911a and 911b. The first mirror plane 660 of the RGO 608 is also the focus point of lens 901 at 608. Without astigmatism, this focus could be at either mirror plane 660, 661 of the RGO 608, or between them. In some implementations, the focus may be at the second mirror plane 661, with gaps between the mirrors.

If an astigmatism is applied, a cylindrical lens with power in the steering axis (steering cylindrical lens 910) is positioned to be equidistant from (equal to the lens focal length) the SAM and the first plane 660 of the RGO mirrors and not be at the centre plane of mirror 909a and 909b. The lens and mirror 909a and 909b with power in the dispersion direction image the light from the SAM to the second mirror plane 661 of the RGO 608. The steering mirror 910 may then image SAM 604 as a Fourier conjugate plane on the first mirror plane 660 of RGO 608. Light from the RGO to the second SLM plane then passes through dispersion axis cylindrical 4F mirrors 911a and 911b to image the second gap optic mirror plane 661 to the second programmable deflection plane. A steering axis cylindrical lens 912 is then positioned to create a Fourier conjugate plane of the first mirror plane 660 of the RGO 608 to the second programmable deflection plane 610. Steering mirror 912 is not in the central plane of mirrors 911a and 911b.

Light then passes back to the RGO 608 and passes through the gap to the output three element anamorphic telescope 914 and to the output ports 602a, 602b.

If an astigmatism is applied, the steering focal plane is not at the gap position because of the astigmatism. Modification to the gap width can be made to take this into account. The anamorphic telescope is designed to create a single focus with a circular beam shape. The 4F dispersion lenses can focus the gap of the gap optic to the focus and the steering axis lens focusses the shifted steering direction focus to the new common focus point to access the output ports.

Figure 6(b) shows a detail of how the RGO 608 can be constructed with this layout. In this arrangement three additional flat mirrors 651, 652, 653 are used with the mirrors of the two planes of the RGO to direct light in the appropriate directions. The pairs of mirrors relating to a single path can then be parallel.

Figure 10 shows an alternative layout structure that can achieve the same results as that of figure 9(c). In this case, the optical system with the grating has only one steering lens 905a. An advantage of this system is that there are two less components in the system with improvements in tolerancing, fabrication and loss. There is no conjugate Fourier image of the first programmable deflection plane 606 at the grating. Other layouts with one, three, or more steering lenses are also possible.

The following sections describe transit optics that can be used with the twin adWSS system utilising the remapping gap optic of figure 6(b) and related figures described above. The transmission optics for both the input and output ports are integrated and the ports are only spatially separated at the first programmable deflection plane(s) and the RGO. This RGO optic lies in the image conjugate plane of the first programmable deflection plane(s). It is not possible to separate the selected ports in the image conjugate plane of the second programmable deflection plane (i.e. the SAM or grating) or the second programmable deflection plane.

For a ROADM switch, there is a selected deflection of the first deflection plane that selects for transit, direct to the output of the other WSS system. Thus there will be spatial position(s) in the image conjugate plane of the second deflection plane (i.e. SAM or grating) that can be sampled with a mirror to the transit optical element group. The position for transit from the input to and position to the output can be the same (but need not be). They are selected from the same set of, or overlapping set of, spatial positions in the SAM or grating plane.

The following description concerns the optics of the transit for the RGO based twin adWSS to make a ROADM system. The optical system may be, for example, a four-element system or a six-element system. The four-element and six-element systems described below concern switched transit, where the transit is in effect an NxN WSS with two demultiplexed deflection planes (the two first programmable deflection planes of the two WSS systems of the twin system). Data can be freely switched between ports. In this case, when doing so, two channels with the same frequency band cannot occupy the same output port. While the six-element system is more complex, it has lower loss. For each of these systems the adWSS layout shown in figures 9(a) to 9(c) will be considered, which is chosen because there are two planes that contain an in-focus conjugate Fourier image of the first programmable plane in the steering direction, and also preferably in focus in the dispersion direction (though this is not a requirement). Thus the two different transit systems (four-element and six-element) for each of the two conjugate Fourier planes (at the SAM 604 and at the grating 907) are described in the embodiments below.

The layout of Figure 10 only meets this condition (i.e. contains an in-focus conjugate Fourier image of the first programmable plane in the steering direction) at the split aperture mirror 604. However, both transit systems (four-element and six-element) will work in this layout at this position and the split aperture mirror embodiments can equally apply to this layout. Indeed, any layout that that has a plane that contains an in-focus conjugate Fourier image in the steering direction of the first programmable deflection plane 606, where the images from the two WSSs are coincident or overlap, can apply a transit system of the types described herein. It is not necessary that this plane be in the same place as the grating 607 or mirror 604, or any other element. In this common plane can be placed a transit port mirror directing the transit port light to the transit optics (the transit optical element group).

It is also not necessary that the dispersion plane is in focus in this plane. Appropriate dispersion optics can be applied so that the light propagating back is in the same optical condition as the light entering so that a proper focus can be achieved at the first programmable deflection plane spectral plane of the opposing WSS to allow coupling into the output ports.

In the case of the four embodiments described below, the dispersion plane is also in focus, and is the preferred arrangement, which simplifies the dispersion cylindrical lenses in these embodiments.

Figure 11 shows a ROADM implementation of the embodiment of figure 5(a) with an addition of a transit optics device 612 at the SAM 604. The transit optics device 612 comprises a group of optical elements to enable the transit of one or more beams between one WSS system and another WSS system, for example between two WSS systems in a twin optical switch, or other MxN optical switch. Here, the ports at 613a, 613b are input or output transit ports. The ports at 614a, 614b are add ports 614a and drop ports 614b. In the RGO 608, the two RGO remapping schemes presented in figure 5(b) can be used, where the group of ports from one WSS can be in separate columns or the top and bottom parts of those columns. Both are possible but in all subsequent embodiments the two separate columns (as shown on the left in Figure 5(b)) are assumed.

The following four embodiments are described only in reference to their transit path and not the add/drop path, which is described above. The design of the RGO 608 in this case is not different from that of the embodiment of figures 9(a)-(c) and subsequent embodiments, as it lies in the add/drop path.

Figure 12(a) shows an implementation of the transit optics in an RGO layout described in figure 11 with the transit optics device 612 branching from the SAM 604. Elements 1100-1106 are flat mirrors. Other components have the same numbering as used previously. In this example, the transit optical element group (612 shown in Figure 11) is configured to receive one or more beams (1 to N beams, e.g. N beams for full NxN switching transit) from the SAM

604. The other deflected beams got to the drop ports. In this example, the transit optical element group 612 is configured to receive four beams from four transit ports. This is exemplary and other numbers of beams and ports are possible. The transit optical element group 612 comprises a transmit steering cylindrical lens 1201a and a transit dispersion cylindrical lens 1201b, a wedge reflector 1202 and a transit steering reflector 1203. A SAM arrangement that may be used with this layout is shown in figure 12(b). The upper and low mirrors of the SAM 604 are shown at 604a and 604b respectively and a single additional mirror 604c is used for the integrated input and output transit ports to one side of the aperture (gap) 1201 in the mirror. The gap 1201 is for the passing of the incidence fan-in beam from the fan lens 603. The beams indicated at 1202 are beams from the four transit ports near the aperture 1201 and are directed to the transit optics 612. The RGO design of figure 6(b) and subsequent diagrams are unchanged in this design over the previously described twin design. While it is possible to have a transit with different number of ports for input or output, it is preferred that the number of input transit ports is the same as the number of output ports, as is typical for a ROADM. In this example, there are four input transit ports and four output transit ports (N=4).

In this implementation, the N transit port images at the SAM 604 have the input N ports and output N ports coincident but separated by an angle. Each transit port image at the SAM plane has 2N beams separated by an angle, so the N input ports are all directed “upwards”, for example. In order to access the N output ports, a Fourier conjugate of these is created with the same steering waist size, and the subsequent N images are then re-imaged to the same place on the SAM as the input ports, but with the beams angled “downwards” at each location towards the output port locations.

The opposite configurations where the input N ports are “upwards” and the output N ports are “downwards” is also a possible arrangement (and there are also other possible arrangements). To achieve this, a transit dispersion cylindrical lens 1201b, a transit steering cylindrical lens 1201a, a transit steering cylindrical reflector 1203 and a custom wedge reflector 1202 with the wedge in the steering direction can be used, as shown in the arrangement of figure 12(a).

Therefore, in this implementation, the transit optical element group comprises, in order from the split aperture mirror 604, a steering lens 1201a, a dispersion lens 1201b, a wedge reflector 1202 and a steering reflector 1203. Beams reflected by the steering reflector 1203 pass through these components in the opposite order back towards the SAM 604, while also forming an image conjugate plane.

Figure 13(a), 13(b) and 13(c) show detail of two implementations using four-element transit optics from the SAM 604 in the steering axis. In this case the N (where N=4 in the diagram) transit input ports, shown at 1301 in Figure 13(a), are on one side of the SAM aperture and the ports are all adjacent to each other. The transit ports 1301 are preferably chosen closest to the aperture of the SAM to minimise loss in the transit. The input port at the fan-in location is shown at 1302. The add/drop ports are shown at 1303. The same optical principle also applies to the grating application and this summary also applies to this (described in a later section). One complication of this system is that the image of the deflected ports from the input transit ports arriving at the split apertures are coincident with the image of the deflected ports required to pass to the output transit ports. The difference between the two is angle. The input transit port directions are all from ports above the optical axis, so they would all have certain incident angles (for example all negative) in the steering axis relative to the optical axis at the split aperture mirror. The output transit port images would similarly have certain angles (for example all positive) in the steering axis direction relative to the optical axis, none of which are the same as any of the input transit angles. Herein, the case is considered where all the input transit angles are negative and output transit angles are positive. Other sets of angles are possible and can be accommodated using a different design of wedge reflector 1202. The wedge reflector 1202 can have two sections 1201a, 1201b which have differently angled surfaces at the input.

The image of the N input transit ports 1301 on the transit port mirrors of the split aperture mirror 604 (all incident with a negative angle in the steering axis) are imaged by a transit steering cylindrical lens 1201a, with power in the steering axis, to form a Fourier conjugate plane at wedge reflector 1202. As the input transit ports at the SAM 604 are negative in angle, the image on the wedge reflector 1202 is all in the lower section, show at 1201b.

The wedge reflector 1202 is a reflector and reflects 90 degrees towards the transit steering reflector 1203. It is drawn in figures 13(a)-(c) as transmitting for clarity but this is not the case in practice. It alternatively is possible to use a refracting prism, or any other method of deflecting a beam by a fixed amount. At the wedge reflector 1202, there is an image of both spectral planes on the first programmable deflection plane. The transit steering reflector, which may be a cylindrical mirror, can be chosen to give 1:1 magnification in the steering waist for all of the embodiments described herein.

In this example, the wedge reflector 1202 comprises a sloped upper section 1202a and a flat lower section 1202b as a mirror. The axis of the rotation of the surface to create the sloped section 1202a is in the dispersion direction and the angle of the slope is in the steering axis. The flat section 1202b for "downwards" incident light is on the same side as the position of the transit ports 1301 and vice versa for the "upwards" incident light. The lower part 1202b of the wedge reflector is flat and reflects the Fourier image of the "downwards" incident light without deviation towards a transit steering reflector 1203, which is a cylindrical mirror with optical power in the steering axis. The transit steering reflector 1203 is positioned one focal length away from the wedge reflector 1202 so that it forms a Fourier conjugate image on the top part 1202a of the wedge reflector. This image on the upper part 1202a of the wedge reflector 1202 is an inverted image of the SAM plane from the input transit ports 1301. This is because the image has passed through a 4F arrangement in the steering direction (1201a and 1203). Thus an inverted image is formed.

The wedge reflector upper part 1202a then applies a negative angle to the beams. The image then propagates through the transit steering cylindrical lens 1201a to form the conjugate Fourier image of the input transit to propagate in the correct position and direction to the transit output ports from the SAM transit mirrors. The system can alternatively operate without the wedge reflector. In this case, the output image is formed at the SAM on the other side of the gap 1302 and N fewer drop ports can be used, as 2N port locations are used for an NxN transit, and greater deflections for more ports results in a higher loss.

In the case that the output transit ports 613b have the same angular ranges at the SAM as the input transit ports 613a, for example if the input transit and output transit fibres have the same pitch in the same mounting. It is not required but is the most likely implementation of this arrangement. To do this, there are certain conditions to be met so that this steering propagation happens as the angles are added and subtracted in conjugate Fourier planes.. The first condition is the focal length of the transit steering reflector 1203 is chosen so that the steering axis waist size at the lower 1202b and upper 1202a parts of the wedge reflector 1202 is the same, which can be chosen from Gaussian formulae: $f = \pi W^2/\lambda$, where W is the steering waist at the wedge reflector and λ is the wavelength. The second condition is that the focal length of the transit steering cylindrical lens 1201a has a focal length equal to that of the transit steering reflector 1203. The third condition is that the angle added to the beams at the lower part of the wedge reflector 1202 is equal to the full angular range of the input transit port spot at the SAM 604.

In the cases where the steering waist at the SAM 604 is too large (or small) to give a reasonable value of focal length, then an anamorphic telescope can be used in the optical system to change the waist size to the ideal value, or an appropriate additional of multiple steering lenses in the grating path.

In the dispersion direction, the system is straightforward in that it has a transit dispersion cylindrical lens 1201b with power only in the dispersion direction. The focal length of this lens 1201b is 1.5x the focal length of the transit steering cylindrical lens 1201a. Along with the transit steering reflector 1203, this would be a 4F imaging system between the input and output image locations ensuring similarity of beam waist size. An additional 4F dispersion lens arrangement can be added if the length to too long such that the width of the beam in the dispersion direction is too wide.

A four-element transit section can be used with a choice of transit ports either side of the aperture in the SAM if a gap optic that removes the gap using a mirror array is applied instead of a SAM. The four-element transit would then apply from additional mirrors to the transit direction in the second mirror plane of the gap optic. A gap optic of this form is shown in figure 13(b).

In figure 13(b), the SAM 3307 is a device which alters the configuration of beams incident on it so as to in this case remove a gap between a first set of those beams and a second set of those beams. The SAM 3307 may be the optical structure 2502 previously described. The SAM 3307 comprises a mirror array. The exemplary SAM 3307 seen in figure 13(b) comprises a first set of two mirrors 3307a, 3307b separated by a gap and a second set of mirrors 3307c, 3307d spaced apart from the first set of mirrors, the second set of mirrors being positioned without a gap between them. In this example, the first set of two mirrors 3307a, 3307b are displaced from one another in the steering direction, with a gap between them along the steering axis. The second set of mirrors 3307a, 3307b are displaced from one another in the steering direction, without a gap between them along the steering axis. A portion of optical signals incident on the device are incident on the mirror 3307a and a portion is incident on the mirror 3307b.

Figure 13(b) shows that input light is focused by the fan lens 3203 so that it passes through the gap between mirrors 3307a and 3307b. In other words, the input light passes by the SAM 3307 without being deflected. Once the light has been deflected by the programmable deflection plane 3204 and has passed back through optical system 3205, the deflected light is intercepted by one of mirrors 3307a, 3307b of the SAM 3307. The light is reflected by one of the mirrors 3307a, 3307b onto one of mirrors 3307c, 3307d. Figure 13(b) shows a portion of the light which is reflected from mirror 3307a onto mirror 3307c. Other portions of light will be reflected from mirror 3307b to mirror 3307d. The reflected light is further reflected by mirror 3307c. The light is thus deflected by the SAM 3307 such that it is directed away from the input light and such that the light is split into two separate sets of beams. In Figure 13(b), the steering lenses are not shown, but are present, with either one or three lenses generally being used. This arrangement enables the possibility of selecting N port positions either side of the gap as the transit ports, which are the N lowest loss port positions. The two mirrors 3350, 3351 at the transit port selection are positioned either side of the gap and send light to two mirrors without a gap on the second plane. The light from the selected ports then transits to the four-element system via two transit direction mirrors 3360a and 3360b. Mirror 3360a accepts light from mirror 3350 and is parallel with it. Mirror 3360b accepts light from mirror 3351 and is parallel with it. Mirrors 3360a and 3360b are not parallel with each other, nor are mirrors 3350 and 3351.

The wedge reflector 1202 is then symmetric with half the slope shared between the two sides 1202a and 1202b, and the four-element system operates otherwise as described and is shown in figure 13(c). The port 1302 for the fan-in location is removed by the SAM mirror arrangement that removes the gap, as described above.

Figure 14(a) shows the operation of the transit ports 613a, 613b with respect to the rest of the system in the dispersion direction. The components have the same numbering as used previously. In this example, the transit optical element group comprises a single dispersion cylindrical lens 1201b positioned half way from the SAM 604 to the transit steering reflector 1203, with a focal length equal to the distance between the SAM 604 and the dispersion cylindrical lens 1201b. This single lens 1201b forms a 4F imaging with unit magnification to the output at the SAM 604.

Figure 14(b) shows the same system from the steering direction. Light from the “top” N (N=4 in this diagram) input ports 613a form an image of the top N spectra in this example on the first programmable deflection plane 606 (which as described above may be a SLM, such as an LCoS). The steering lens images the selected port location on the SAM 604. The beams from the transit ports are directed to the transit optics by the sample mirror in figure 12(b). A transit steering cylindrical lens 1201a forms a Fourier conjugate of the SAM plane on the wedge reflector 1202. This will then be the same positional information as the spectra on the first programmable deflection plane 606, and thus N points are formed on the upper part 1202a of the wedge reflector 1202 as the beams here are “upwards” from ports above the aperture of the SAM 604, hence the slope part 1202a of the wedge reflector is on the same side of the axis as the transit ports. The wedge reflector 1202 can be a mirror reflector or a refraction prism that imparts a negative angle of the appropriate amount. A transit steering reflector 1203 then forms a conjugate image of the wedge reflector 1202 back at the wedge reflector 1202. The focal length of this lens 1203 is such as to form the same waist in the steering direction as in the original beam at the wedge reflector 1202. The wedge reflector 1202 reflects the beams without deviation. The beams then are reimaged back through the transit steering cylindrical lens 1201a to the same locations but with a “upwards” beam so that they now access the output ports.

Figure 15(a) shows a layout of a SAM transit utilising a six-element transit system. The components are the numbered the same as previously. In addition to the components from the four-element transit system described previously, the six-element transit system has one additional transit steering cylindrical lens 1201c and an additional wedge prism 1204. 1100-1108 are flat mirrors. Therefore, in this implementation, the transit optical element group comprises, in order from the split aperture mirror 604, a first steering lens 1201a, a wedge reflector 1202, a transit dispersion lens 1201b, a second steering lens 1201c, a wedge prism 1204 and a steering reflector 1203. The advantage of this system is that it allows the arbitrary choice of ports either side of the aperture in the split aperture mirror 604. One possible selection would be the N/2 ports either side of the aperture which would have a significantly lower loss that all N ports on one side. Thus this six-element arrangement offers a lower loss than the four-element transit optics without using the two mirror planes of Figure 13(b).

Figure 15(b) shows the SAM design for the case where the two ports top and bottom are chosen for transit (the case where N=4 is shown). These ports are indicated at 1501. This SAM comprises two additional transit deflection mirrors 604d and 604e at the SAM 604 with a gap 1201 between.

Figure 16(a) shows further detail of the six-element transit optics in the steering direction that can be applied in this case where equal numbers of ports are chosen either side of the central aperture 1201 of the SAM 604 in Figure 15(b) (i.e. N/2 ports on each side). Multiple lenses can be used to reduce divergence in the dispersion direction. That is, further lenses can be used in addition to transit dispersion cylindrical lens 1201b. In this example, the wedge reflector 1202 has two sloped sides 1202a and 1022b. Wedge reflector 1202 adds equal and opposite angles to beams to separate them on the wedge prism 1204, after passing through lenses 1201b and 1201c. At the wedge reflector 1202 is an image plane of spectra on the first programmable deflection plane (with no gaps). Wedge prism 1204 deflects beams to image to opposite side but also deflects and corrects outer beams so that the gap is removed in the input and created in the output. At the wedge prism 1204 is an image of the split aperture mirror plane split into two input/output planes (without gaps). In this case the beams at the SAM 604 from the WSS incident propagate “downwards”. As this system is symmetric either side of the optical axis is this direction, “upwards” and “downwards” does not change the design.

It should be noted that this six-element design is particularly suitable if there is no gap between the spectra in the first programmable deflection plane. This would be the ideal case. A four-element design may be used if there is a part of the spectral plane that has a gap, the size of a spectra, in the column of spectra. This gap would then map as a Fourier conjugate to the gap in the ports in the SAM plane, so can be used with transit ports either side of the gap and with a SAM as shown in Figure 15(b).

The incident light passes through a steering cylindrical lens 1201a to form an image on the lower part 1202b of the wedge reflector 1202. This reflector has the two equal and opposite slopes in the steering direction, imparting an angle in each case towards the optical axis of an amount equal to the full range of angles at the SAM of the incident beams (the slope angle on the mirror would be half this). This wedge reflector 1202 will have an image of the first programmable deflection plane on it. The light them propagates through a dispersion cylindrical lens 1201b and second steering cylindrical lens 1201c to form an image of the SAM plane on the upper part of the wedge prism optic 1204.

Such a prism 1204 is shown in figure 16(b), but many different optics can achieve this such as a mirror array, microlens/lens system, diffractive or holographic optical element, freeform elements or a mix of the above.

This optical element 1204 removes the gap (image of the aperture in the SAM plane) between the separate groups of images. This can be done with two prism surfaces for the upper two beams that are different from two prism surfaces for the lower two beams. There is greater refraction from the top beams and correction surface and lesser reflection from the lower beams. The increased convergence and corrections means that after this element, and image of the transit ports without the gap is formed. The beams 1601 in Figure 16(b) are the input beams with a gap (image of SAM location) and the beams 1602 are the output beams without a gap.

The light then propagates by the transit steering reflector 1203 to form an image of the Fourier conjugate plane at the lower part of the wedge prism. The propagation back to the SAM is then the same in reverse for the returning beams as for the incident beams. There is an overall correction downward for all beams to ensure the beams are imaged correctly through transit steering reflector.

The focal lengths of the two steering lenses and steering reflector are equal and equal to $f = \pi W^2/\lambda$, as defined in the previous section. Other requirements are the same.

In the dispersion direction all the conditions and variations also apply in this case, only that the dispersion lens sits half way between the SAM and transit steering reflector with a focal length 2.5x that of the steering lenses.

Figure 17(a) shows the operation of the transit ports with respect to the rest of the system in the dispersion direction. The transit is straightforward in positioning a single dispersion cylindrical lens half way from the SAM to the transit steering reflector, with a focal length equal to the distance between the SAM and the dispersion cylindrical lens. This single lens forms a 4F imaging with unit magnification to the output at the SAM. Multiple dispersion lenses can be used in order to form an image in a reasonable distance. The number of dispersion lenses may be inverting or non-inverting, as the beam is generally symmetric in the dispersion direction.

Figure 17(b) shows the same system from the steering direction. Light from the “top” N (N=4 in this diagram) input ports form an image of the top N spectra in this configuration on the first programmable deflection plane 606. The steering lens images the selected port location on the SAM 604. The transit ports are directed to the transit optics by the sample mirror in figure 15(b). A transit steering cylindrical lens 1201a forms a Fourier conjugate of the SAM plane on the wedge reflector 1202. This will then be the same positional information as the spectra on the first programmable deflection plane 606, and thus N points are formed on the upper part of the wedge reflector 1202 (as the beams here are “upwards” from ports either side of the aperture of the SAM. The wedge reflector 1202 can be a mirror reflector or a refraction prism that imparts a negative angle of the correct amount towards the optical axis.

A further steering cylindrical lens 1201c makes a further conjugate Fourier image onto the lower port of the wedge prism 1204. The wedge prism 1204 removes the gap in the image plane here as shown in figure 16(b). A transit steering reflector 1203 then forms a conjugate image of the wedge prism 1204 back at the wedge prism upper section. The focal length of this lens is such as to form the same waist in the steering direction as in the original beam at the wedge reflector 1202. The beams are then propagated similarly back to the SAM 604 in the proper format to propagate back to the first programmable deflection plane 606 to be directed to the output ports.

Figure 18 shows the block diagram of the same system from figure 5(a) with the ROADM implementation utilising the NxN transit 612 at the grating multiplexer in block 605. As with the previous embodiment, the RGO 608 design is unchanged in this design.

Figure 19(a) shows the layout of an adapted system of figure 9(a)-(c) and the four-element transit optical system emergent from the grating 907a, using the single sample mirror 1950 shown in figure 19(b). The transit mirror plane is the plane of the transit mirrors 1950 in Figure 19(b). The operation of the transit optics is identical to that of figure 13(a), though the transit dispersion lens should be wide enough to cope with the demultiplexed data.

The sample mirror 1950 at the grating 907a in figure 19(b) does not need to be at an angle to the grating, as light typically is directed at the grating at an angle in the dispersion direction (the Littrow angle of the grating for optimum performance) allowing the mirror 1950 to be parallel and in contact with the grating 907a and allow propagation to a different path for the transit optics. Typically the steering waist at the grating is larger than at the SAM and less controllable so the transit optics would tend to be longer, and this is reflected in figure 19(a). Figures 19(c) and 19(d) show layout diagrams for the dispersion and steering directions for this arrangement, with components numbered as previously.

Figure 20(a) shows the layout of an adapted system of figure 9(a)-(c) and the six-element transit optical system emergent from the grating 907b, using the sample mirror 1950 in figure 20(b). The operation of the transit optics is the same as that of figure 16(a), though the transit dispersion lens needs to be wide enough to cope with the demultiplexed data.

Because of the likely long path for the transit in this arrangement, figure 20(a) illustrates the use of three dispersion cylindrical lenses 2000a, 2000b, 2000c in the arrangement to control the demultiplexed beam width in the dispersion direction through the transit optics. Alternatively, one or more of the transit dispersion lenses may be a spherical lens. However, any number of dispersion lenses (e.g. one or more than three) can be used instead. This arrangement also uses two transit steering lenses (which may be cylindrical or spherical lenses), shown at 2000d and 2000e. Other components are numbered the same as previously.

The sample mirror 1950 at the grating 907b in figure 20(b) comprises two transit mirrors 1950a and 1950b. The mirrors do not need to be at an angle to the grating, as light typically is directed at the grating at an angle in the dispersion direction (the Littrow angle of the grating for optimum performance) allowing the mirrors to be parallel and in contact with the grating and allow propagation to a different path for the transit optics. Typically the steering waist at the grating is larger than at the SAM and less controllable so the transit optics would tend to be longer, and this is reflected in figure 20(a). Figures 20(c) and 20(d) show a layout diagram for the dispersion and steering directions for this arrangement.

Figure 21(a) illustrates an arrangement similar to figure 19(a) whereby the transit optics is linked to the grating 907c through a gap optic arrangement with flat mirror 1150 in the diagram. As shown in figure 21(b) the reflection mirrors 1950a, 1950b and the subsequent flat mirror 1150 can form two mirror planes of a gap optic that removes the gap that exists at the grating plane. The gap optic is of a similar mirror arrangement shown at the SAM plane in Figure 13(b). The transit optics in this case are shown in Figure 21(c) and function identically to that illustrated in figure 13(c) with the SAM plane replaced by flat mirror 1950 as the second plane of the gap optic.

In the case of the embodiments described previously, all refer to transit schemes that offer a full NxN switch between all the demultiplexed channels of the N input to the N output transit ports. This uses N output ports for the transit, so for a N degree ROADM with M switching locations, there are M-N add and drop ports. It is possible to use a number P of LxL switches between transit ports, where P=N/L and P and L are integers, which limits the switching between the transit ports. In this case only L switching ports are used meaning for the N degree ROADM there are M-L add and drop ports. This allows less switching locations in the spectral plane and lower loss ports in the add/drop path.

The simplest application is where L=1, a 1x1 switch i.e. a direct connection between the input and output transit ports without any switching and is illustrated in figure 22. In this case the non-dropped channels from one transit port, such as port 2201, are sent directly to one output port, such as port 2202, merged with add data that must correspond with any channels not used or dropped. In this case there is only one switch position from the first programmable deflection plane (e.g. SLM) spectral plane that relates to a transit at the minimum loss port. The following descriptions relate to arrangements of the twin add/drop WSS that have non-switched transit, embodying figure 22. The description will only refer to the transit traffic, the add/drop traffic already explained prior to this.

Figures 23(a) and 24(a) illustrates a layout based on the layout of figure 9(c), though could equally apply to that of figure 10 or any layout which forms a conjugate Fourier plane of the switching spectra on the first programmable deflection plane, the conjugate Fourier plane forming an image of port locations whose position is determined by the switching angle at the SLM. For the optical arrangement between the split aperture mirror and first programmable deflection plane based on Figure 9(c) has two places where a conjugate Fourier plane exists, at the grating and at the split aperture mirror. In this case one of the switching locations (and hence located in a unique spatial position in the conjugate plane) is designated a transit plane and any channel from the input ports is deflected at the required angle in order to transit.

Figure 23(a) illustrates a layout that enacts a non-switched transit according to Figure 22 at the split aperture plane. The arrangement requires no additional optics and only requires a modification to the split aperture mirror with a flat mirror or retroreflecting structure reflecting the light back along the same path to the first programmable deflection plane (figure 23(b) shows an example, but of course any port can be chosen).

The split aperture mirror 2300 has a transit return at sections 2300a and 2300b that directs light to add/drop path, and one port location back to transit. The transit mirror 2300c returns light back along the same path at one port location. There is a gap, shown at 2350, for fan beam incidence.

As the split aperture mirror is in a conjugate plane, the light will reach the SLM after passing through the equivalent of a single 4F lens system in the steering direction so an inverted image is formed of the original spectra, aligned with the spectra emerging from the add ports. The channels are then directed to the output ports with the correct deflection relating to the gap through the split aperture mirror. The light is multiplexed at retroreflection so the orientation of the spectrum in the dispersion direction is the same as the first set of spectra. The operation of the transit selection 2300c of the SAM 2300 for figure 23(a) is shown in figures 23(c) and 23(d) for the dispersion direction and steering directions respectively. Other components are numbered the same as previously.

In this arrangement the light in transit passes the diffraction grating four times but only interacts with the first programmable deflection plane 606 and the add/drop path not at all. This reduces latency and insertion loss for the transit traffic.

Figure 24(a) illustrates the layout where the transit is enacted for light passing from the first programmable deflection plane 606 before reaching the diffraction grating 907. In this example, the transit optical element group comprises two transit cylindrical steering lenses 1201a and 1201c, transit dispersion cylindrical lens 1201b and a transit flat reflector 2400. In this case, a transit mirror 2401 can be placed at the location of the switchable port in the conjugate plane just before the grating 907d (figure 24(b)). The mirror 2401 does not need to be raised or angled to pass the light to the transit optics, as the light usually is incident at the Littrow angle of the grating off axis (for optimum efficiency of diffraction), which means the reflection from a mirror parallel to the grating surface will pass into a separate optical path. However, a prism or offset mirror can alternatively be used. The mirror 2401 can be placed on the other side of the grating 907d so that the mirror reflects multiplexed data. The optical system would then follow the description of figure 23(a) as a simple mirror retroreflection.

A simple mirror can be used before the grating, however reflecting demultiplexed data in this manner would reflect an inverted image of the spectra in the right place in the steering direction but in an inverted orientation opposite to the input spectra on the SLM. This light would then need to pass through a different grating or the same grating (if the design allows it) with a different optical order (the opposite optical or negative order of diffraction compared to the input spectra, using the opposite Littrow angle in the dispersion plane).

For transit to the same port mirror location shown in figure 24(b), the operation of the transit optics are shown in figures 24(c) and 24(d) for the dispersion and steering directions respectively. This will involve a single cylindrical dispersion lens midway between a flat mirror or retroreflector. The focal length of this lens is the same as the distance to the mirror or the gap in the grating, the optical axis of the lens being aligned with the gap. Two cylindrical lenses with power in the steering direction in a 4F arrangement between the mirror and the gap in the grating. The focal length of each lens can be half that of the cylindrical dispersion lens in the transit. Two passes through a 4F imaging system will ensure that the image is non-inverted and so can use the same mirror to recouple to the output. This transit optical layout can also be used at the split aperture mirror instead of the transit optics of figure 23(a) with the same split aperture mirror as in figure 23(b).

A simpler optical arrangement is shown in Figure 25(a) where the transit optical element group comprises a single spherical lens 2550 one focal length from the gap of the grating 907e and in alignment with it, and also a flat mirror 2400 as the transit reflector. The image is in the correct orientation for re-multiplexing in the dispersion plane but an inverted image in the steering direction. Mirrors 2500a, 2500b can be used at this place, as shown in figure 25(b) for propagation to the output SLM plane. The operation of the transit optics are shown in figures 25(c) and 25(d) for the dispersion and steering directions respectively. The advantage of this is simpler transit optics at the expense of losing both of the lowest loss ports and increased fabrication complexity of the transit mirror plane at the grating.

In these cases the transit light passes through the diffraction grating and SLM only twice and the add/drop path not at all. This reduces latency and insertion loss for the transit data traffic.

Figure 26 illustrates an alternative construction that can replace the split aperture mirror of figure 7. In this case, the light from the input ports 601a, 601b (and optionally a flat mirror) passes to a polarising beamsplitter 2601 so as to be transmitted. The polarising beam splitter 2601 is configured to transmit light at a first plane of polarisation and reflect light at a second plane of polarisation which is orthogonal to the first plane of polarisation. The polarising beam splitter 2601 according to this example is configured to transmit light having a vertical plane of polarisation and reflect light having a horizontal plane of polarisation. The transmitted light from the polarising beamsplitter 2601 having a vertical polarisation passes through a faraday rotator 2602 which rotates the polarisation plane by 45 degrees. The beam, polarised at 45 degrees, is then passed to optical system 605 with a half wave plate to align it with the SLM or grating polarisation requirements. The light is then passed to the first programmable deflection plane 606 according to the grating optics described in previous embodiments. One or more half wave plates (not shown) can also be placed anywhere between the faraday rotator and second programmable deflection plane to correct for any polarisation requirement at the second SLM plane or the grating multiplexer/demultiplexer.

The angle of the light is then deflected by the SLM plane and the light is passed back through the grating optics including any half wave plates and faraday rotator to the polarising beamsplitter 2601. The faraday rotator 2602 rotates the returning light by a further 45 degrees so it is orthogonal to the incident plane of polarisation at the beamsplitter 2601 so the light is then reflected. The light then propagates to the RGO 608 and to the output ports 602a, 602b as defined in the layout designs described above. Further half wave plates can be used for any subsequent polarisation dependence, such as at the second programmable deflection plane. This approach can be used with programmable deflection planes that are already polarisation dependent, and so require polarised input beams, for example LCoS (Liquid Crystal on Silicon) SLMs. The on-axis (undeflected) port can be used in this case as an extra low-loss output port. This can also apply equally to twin add/drop WSSs and ROADM systems with a grating transit.

In some embodiments, the polarising beamsplitter 2601 can optionally not be at the focus of the returning beams. If so, the focus plane can exist at another plane and can include a split aperture mirror to effect a transit as well as redirection. The undeflected on-axis beam can be used for the non-switched transit of figure 23(a) to minimise the loss of transit data. For a switched transit, N adjacent ports can be used with the lowest loss without any optics that deal with a gap. For example the transit optics of figure 13(c) can be used without any gap optics.

The polarising beamsplitter 2601 can also be at the focus of the beams. One advantage in this case is the ability to use the on-axis (undeflected) beam as a usable output port. In this case the beamsplitter 2601 and faraday rotator 2602 can be positioned to accept only the incident beams and the undeflected beams. Deflected beams to the output ports do not pass through the Faraday rotator 2602 or beamsplitter 2601 a second time and instead are deflected by a split aperture mirror of any type described above.. The advantage of not passing through the faraday rotator a second time for the add/drop ports is that the polarisation state will be correct for the second programmable deflection plane for the space switches. Furthermore, there is a reduced loss.

An example of the use of this on-axis port, shown in figure 27, is as the retroreflecting mirror of a non-switched transit, as described for figure 23(a). In this case the reflected on-axis beam simply hits a mirror 2701 and is reflected back to the SLM plane, this time forming an inverted image of the ports on the first programmable deflection plane of the other WSS system. The split aperture mirror is indicated at 604, with the upper mirror shown at 604a and the lower mirror shown at 604b. One group of spectra (either input or output) may pass through a half wave plate to align the polarisations for a polarisation dependent SLM (such as an LCoS). This is optimally placed in an image conjugate plane of the first programmable deflection plane (the same Fourier conjugate plane as the spectral first SLM plane) between the faraday rotator and the SLM plane, for example at the SLM plane itself. The flat mirror 2701 is drawn as separate but is ideally as close as possible to the polarising beamsplitter and can be a reflective layer applied directly on the output surface of this beamsplitter. Alternatively two spherical lenses can be placed between the beamsplitter and the mirror to form a non-inverted image back at the beamsplitter.

The beam shown at 2702 is passed to optical system 605 and is polarised at 45 degrees, which can further be passed through a half-wave plate to align with SLM or grating polarisation requirements, before hitting the first programmable deflection plane 606. The beam shown at 2703 is the returning, undeflected light from the first programmable deflection plane 606 (e.g. SLM), selected for transit. The beam shown at 2704 is the retroreflected beam to the grating or SLM output plane. This beam can be passed through a half-wave plate over the output SLM areas to rotate the polarisation by 90 degrees.

The beams shown at 2705a and 2705b are the deflected beams from the first programmable deflection plane (e.g. SLM). These rays do not pass through the Faraday rotator. These rays are directed to the RGO 608. These rays then have the correct polarisation for the second programmable deflection plane 610 (e.g. SLM).

This arrangement has an advantage of being an automatic non-mechanical “failsafe” mode. If the programmable deflection plane, for example SLM, fails in operation the system defaults to a non-deflected beam state. This arrangement ensures all the data is not lost or blocked but transited straight through un-switched. This allows improved network performance in the event of a failure.

A polarising beamsplitter 2601 can be used with a split aperture mirror 604 if the polarising beam splitter 2601 is not in the focal plane of the beam, as shown in figure 28. In this case the split aperture mirror 604 is at the focal plane of the beams (the line of focus is marked at the split aperture mirrors). The upper mirror shown at 604a, the lower mirror shown at 604b and the central mirror is shown at 604c. In addition a non-inverting image optical system from central split aperture mirror 604c back to the same mirror is applied, as the flat mirror 2701 is far from focus. This can be a 4F configuration of lenses 2801 as illustrated in figure 28. This configuration is less dependant on the package sizes of the faraday rotator 2602 or polarising beamsplitter 2601.

The polarising beamsplitter 2601 can reflect the incident light and transmit the return light or vice versa in operation without loss of functionality with appropriate changes in layout. Note in all of these embodiments, the undeflected light, retroreflected on-axis light and the input beam are coincident even if drawn slightly separate for clarity.

In the embodiments shown in Figures 26, 27 and 28 a grating can be applied with the same functionality, leading to the respective transit optics as described above.

For the optics of the embodiments, they can apply to any plane that forms a steering conjugate plane of the first programmable deflection plane for the input and output WSSs. If this plane is multiplexed, it can follow the optics described for the spilt aperture mirror above and if the beams are demultiplexed, the optics can follow the description of the embodiments for the grating transit above.

The edge ROADM switch described herein incorporates two adWSS or two MxN switches. As previously described, each MxN switch is configured to operate so as to transfer signals from ports 601a to 602a, from ports 601b to 602b, from ports 602a to ports 601a and from ports 602b to ports 601b. The edge ROADM switch also operates so as to transfer signals from ports 601a to 601b and from ports 601b to ports 601a. It is therefore the case that according to one example, light from input ports 601a which is not selected by the first programmable deflection plane 606 for transit is deflected to the output ports 602a. Light is which is selected for transit by the first programmable deflection plane 606 and passes through the transit section is therefore merged with light coming from ports 602b at the second programmable deflection plane 610 and together is output at ports 601b. It will be readily understood that further adWSS or MxN switches could be incorporated into a single switching device. Suitably, the programmable deflection planes described herein are SLM planes. The SLM plane may be a MEMS mirror array. The SLM plane may be an LCoS device. The LCoS device applies a hologram to enable a beam deflection. Alternatively, the SLM plane may be another locally configurable device capable of applying a deflection to a channel from the input.

In the examples described herein, the first and second programmable deflection planes are incorporated onto a single SLM device. This utilises fewer components, reduces control complexity and hence cost compared to if the programmable deflection planes are on separate SLM devices. Alternatively, the programmable deflection planes may be on separate SLM devices.

In the examples described herein, optical components are used to route data through the described switches. There is no absorption and re-emission of light, thereby avoiding the lag associated with transmitting data through electronical switches. The optical components also have lower power consumption than equivalent electronical implementations.

The examples described herein incorporate one or more diffraction grating. However, any demultiplexer which demultiplexes light signals into spatially separated data channels may be used instead of a diffraction grating in any of the examples. Similarly, any multiplexer which multiplexes spatially separated data channels into multiplexed light signals may be used instead of a diffraction grating in any of the examples. Any suitable optical dispersion device may be used as a multiplexer and/or a demultiplexer.

Lenses and other optical components described herein as single structures may be implemented using assemblies having a plurality of components which achieve the same optical effect. Examples of such assemblies are: achromatic doublets, achromatic triplets, Cook doublets, telescopes and microscopes for imaging lenses. The lenses described herein may be implemented using other optics with the same optical power. For example, a curved mirror may be used as a lens. For example, multiple lens elements, mirrors, mirror arrays, catadioptric systems, holographic optical elements or diffractive optical elements may be used as a lens. Separate elements, for example 4F lenses, with the same optical properties can be arranged as separate passes through or from a single physical element.

The examples described herein generally use one or more mirrors. The term “mirror” may be used herein to refer to any reflective surface such as a metallic mirror, an interference layer, a total internal reflection surface (such as a prism), a polarisation beamsplitter, or a diffractive or holographic surface, multiple instances of any of these with the same effect or other known structure. Lenses and mirrors with optical power can be interchangeable with variations in layout. A mirror in one layout can be lens or lens with a flat directing mirror in another layout with the same properties.

Embodiments of the present invention describe a system where the first programmable deflection plane has demultiplexed data and the second programmable deflection plane has multiplexed data. Alternatively, both first and second planes may be multiplexed (no gratings) or both demultiplexed (for example, with gratings in both 4F systems incident on the two SLM planes).

As mentioned above, the first and/or second programmable deflection planes may be SLMs. SLMs can be LCoS, liquid crystal panels, controllable MEMs mirrors or DLP devices. The use of an LCoS as an SLM can also allow flexible channel widths within the band.

Embodiments of the present invention are directionless (can work in both directions), colourless (independent of wavelength) and contention-less (port output selection independent of other port selections).

The applicant hereby discloses in isolation each individual feature described herein and any combination of two or more such features, to the extent that such features or combinations are capable of being carried out based on the present specification as a whole in the light of the common general knowledge of a person skilled in the art, irrespective of whether such features or combinations of features solve any problems disclosed herein, and without limitation to the scope of the claims. The applicant indicates that aspects of the present invention may consist of any such individual feature or combination of features. In view of the foregoing description it will be evident to a person skilled in the art that various modifications may be made within the scope of the invention.

CLAIMS

1. An optical switch comprising a plurality of independently controllable systems, each independently controllable system comprising a set of input ports and a set of output ports, whereby the optical switch is optically configured such that the set of output ports can only receive data from the corresponding set of input ports, each system comprising:

a set of input ports, each input port configured to transport an optical signal having at least one component frequency channel;

a set of output ports corresponding to the set of input ports, each output port configured to transport an optical signal having at least one component frequency channel;

a first programmable deflection plane configured to deflect beams incident thereon to form a corresponding first deflected array of beams;

a second programmable deflection plane configured to deflect beams incident thereon to form a corresponding second deflected array of beams;

a beam steering optical element group configured to transfer the first deflected array of beams between the first programmable deflection plane and the second programmable deflection plane, the beam steering optical element group of each of the plurality of systems comprising a common plane and an optical system between the common plane and the second programmable deflection plane; and

wherein the optical switch is configured to form a Fourier conjugate plane in a steering direction, of the first programmable deflection plane of each of the plurality of systems on the common plane for the plurality of systems, wherein the Fourier conjugate plane of the first programmable deflection plane of one system overlaps the Fourier conjugate plane of the first programmable deflection plane of at least one other system on the common plane; and

wherein the optical system is configured to form an image of each of the plurality of systems, which is a Fourier conjugate in the steering direction, of the first programmable deflection plane on the second programmable deflection plane.

2. The optical switch as claimed in claim 1, wherein the Fourier conjugate plane from the one system is spatially coincident with the Fourier conjugate plane from the at least one other system.

3. The optical switch as claimed in claim 1 or claim 2, wherein the Fourier conjugate plane from the one system is different to the Fourier conjugate plane from the at least one other system.

4. The optical switch of any preceding claim, wherein the beam steering optical element group comprises a split aperture mirror and wherein the common plane is located at the split aperture mirror.

5. The optical switch of claim 4, wherein the split aperture mirror is in an image plane for the first programmable deflection plane.

6. The optical switch of any preceding claim, wherein the beam steering optical element group comprises a grating arrangement and wherein the common plane is located at the grating arrangement.

7. The optical switch of claim 6, wherein the grating arrangement is a component of a multiplexer or demultiplexer of the beam steering optical element group.

8. The optical switch of claim 6 or claim 7, wherein the grating arrangement is in an image plane for the first programmable deflection plane.

9. The optical switch as claimed in any preceding claim, wherein the beam steering optical element group comprises one or more 4F arrangements of optical lenses.

10. The optical switch as claimed in any preceding claim, wherein the beam steering optical element group comprises a Faraday rotator and/or a polarising beamsplitter.

11. The optical switch as claimed in any preceding claim, wherein the first programmable deflection plane of the one system is optically connected to the first programmable deflection plane of the at least one other system of the plurality of systems, and wherein the optical switch is configured such that one or more beams of the first deflected array of beams for the one system propagate to the common plane.

12. The optical switch as claimed in any preceding claim, wherein the optical switch comprises a transit optical element group configured to direct the one or more beams of the first deflected array of beams from the common plane to the first programmable deflection plane of the at least one other system.

13. The optical switch of claim 12, wherein the beam steering optical element group of a respective system is configured to:

transfer one or more of the first deflected array of beams of the respective system from the first programmable deflection plane of the respective system to the transit optical element group; and

transfer one or more of the first deflected array of beams of another system from the transit optical element group to the first programmable deflection plane of the respective system.

14. The optical switch as claimed in claim 12 or claim 13, wherein the transit optical element group comprises one or more steering lenses, one or more dispersion lenses and one or more reflectors.

15. The optical switch as claimed in any of claims 12 to 14, wherein the transit optical element group comprises one or more of a wedge reflector and a wedge prism.

16. The optical switch as claimed in any of claims 12 to 15 as dependent on any of claims 6 to 8, wherein the grating arrangement comprises one or more mirrors configured to direct one or more beams from the first programmable deflection plane to the transit optical element group.

17. The optical switch as claimed in any of claims 12 to 15 as dependent on claim 4 or claim 5, wherein the split aperture mirror comprises a transit mirror configured to direct one or more beams of the first set of deflected beams from the first programmable deflection plane to the transit optical element group.

18. The optical switch of any preceding claim, wherein each beam steering optical element group comprises a remapping optical device comprising *n* sets of:

a first pair of mirrors configured to provide an optical path for a first set of beams of the first deflected array of beams; and

a second pair of mirrors configured to provide an optical path for a second set of beams of the first deflected array of beams, the first and second pairs of mirrors having differently angled surfaces so as to alter the conform arrangement of the first and second sets of beams of the first deflected array of beams to form a remapped array of beams,

where *n* is the number of systems in the plurality of systems.

19. The optical switch of claim 18, wherein the first pair of mirrors comprises a first mirror and a second mirror and the second pair of mirrors comprises a third mirror and a fourth mirror.

20. The optical switch as claimed in claim 19, wherein the first mirror and the third mirror are arranged linearly in the steering direction of the respective beam steering optical element group.

21. The optical switch of claim 19 or claim 20, wherein the first mirror and the third mirror are positioned adjacent to each other such that no gap exists between them.

22. The optical switch of any of claims 19 to 21, wherein the first mirror and the third mirror are part of a first set of mirrors in a first mirror plane of the remapping optical device and wherein the second mirror and the fourth mirror are part of a second set of mirrors in a second mirror plane of the remapping optical device.

23. The optical switch as claimed in claim 22, wherein the first mirror plane and the second mirror plane are linearly aligned for all systems of the optical switch.

24. The optical switch as claimed in claim 22 or claim 23, wherein the mirrors of the second set of mirrors are positioned in a grid, wherein there is a gap between each mirror in the grid.

25. The optical switch of any preceding claim, wherein the optical system comprises a spectral plane which is a Fourier conjugate plane in the steering direction of the second deflection plane and an image plane in the steering direction of the first deflection plane.

26. The optical switch as claimed in claim 25, wherein the common plane, the spectral plane and the second deflection plane are in an image plane of the first programmable deflection plane in the dispersion direction.

27. The optical switch as claimed in claim 25, wherein the optical system comprises an optical element located at the spectral plane which is configured to generate a gap between the beams incident on it in the dispersion direction.

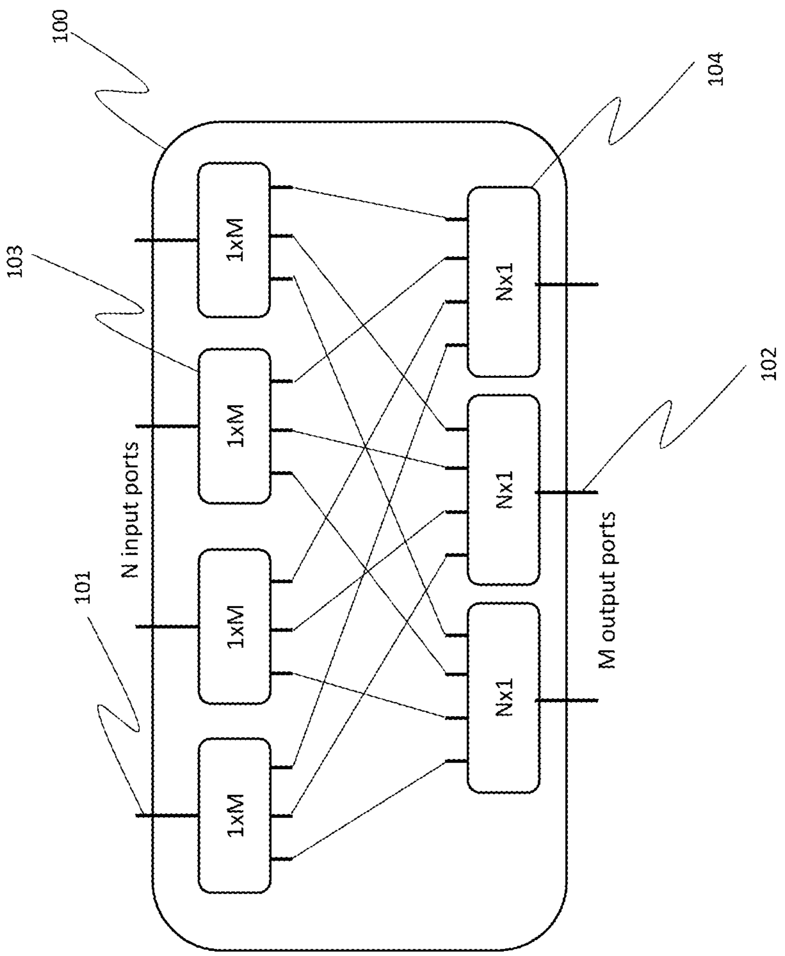
100
103
101
104
102
N input ports
1xM
1xM
1xM
1xM
Nx1
Nx1
Nx1
M output ports

FIG. 1(a)

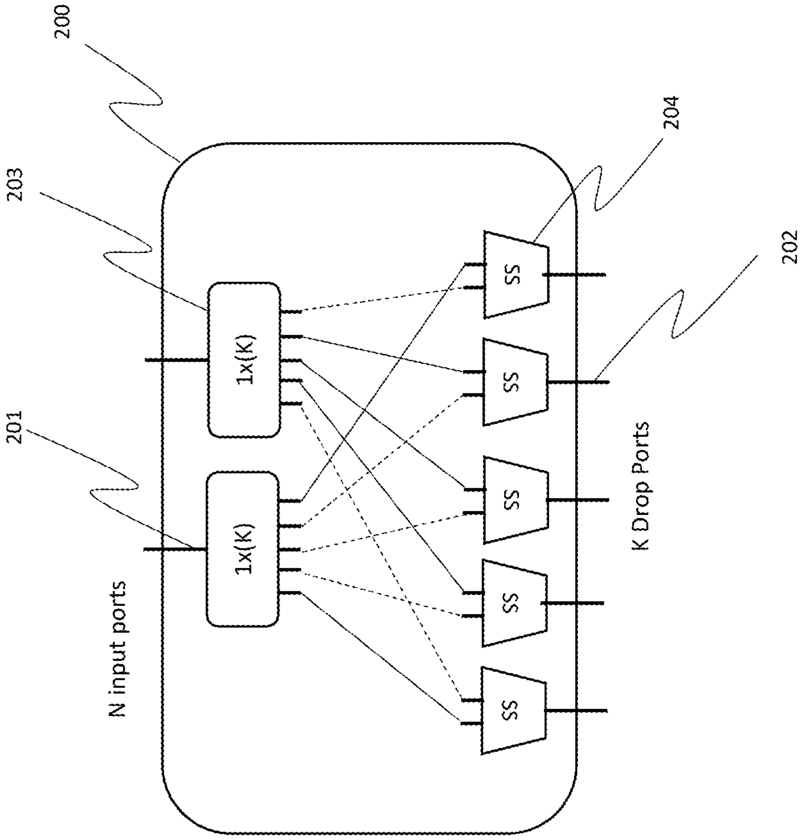
200
203
201
204
202
N input ports
1x(K)
1x(K)
SS
SS
SS
SS
SS
K Drop Ports

FIG. 1(b)

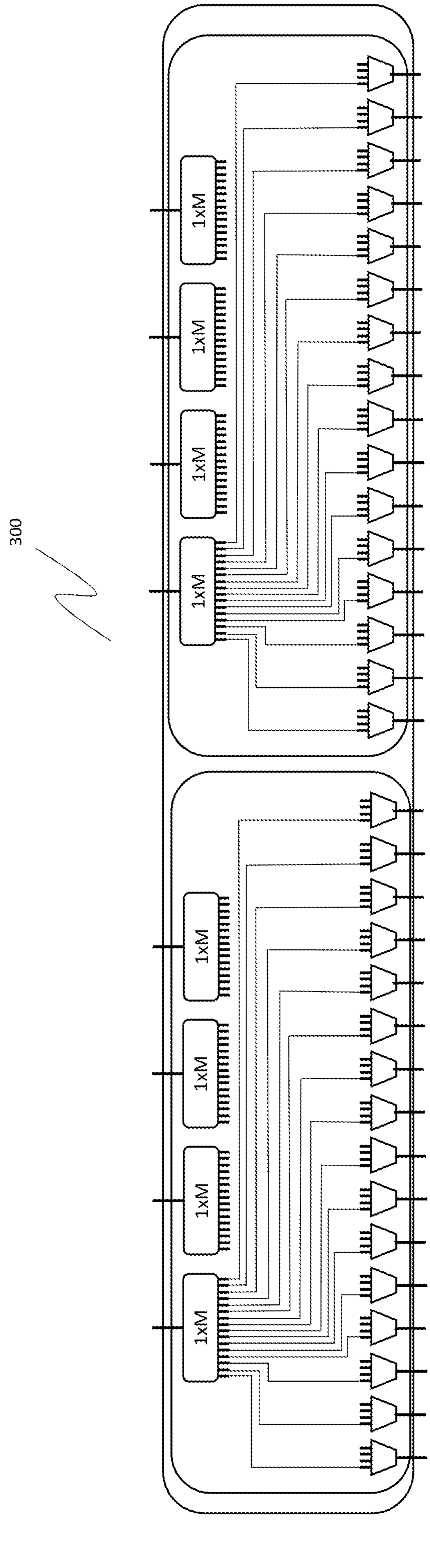

FIG. 2

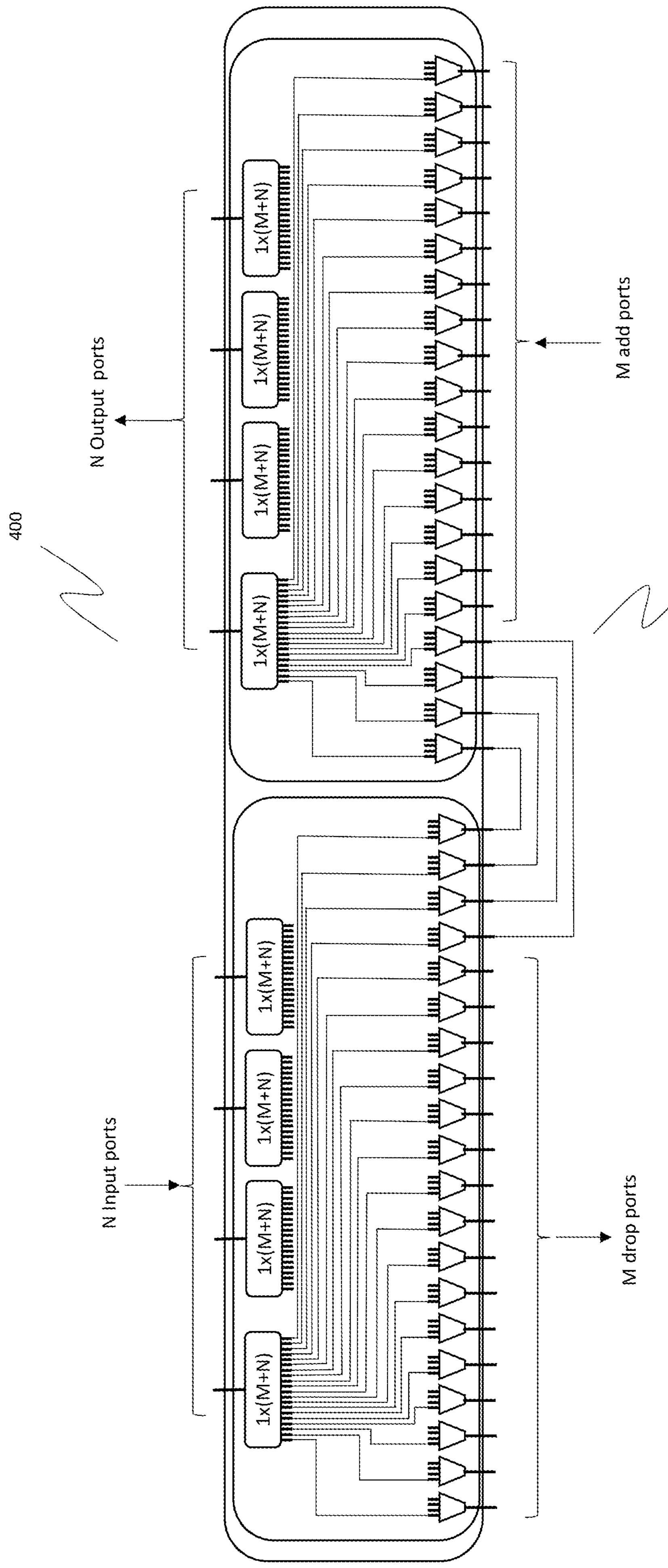
N Output ports
M add ports
400
401
1x(M+N)
N Input ports
M drop ports

FIG. 3

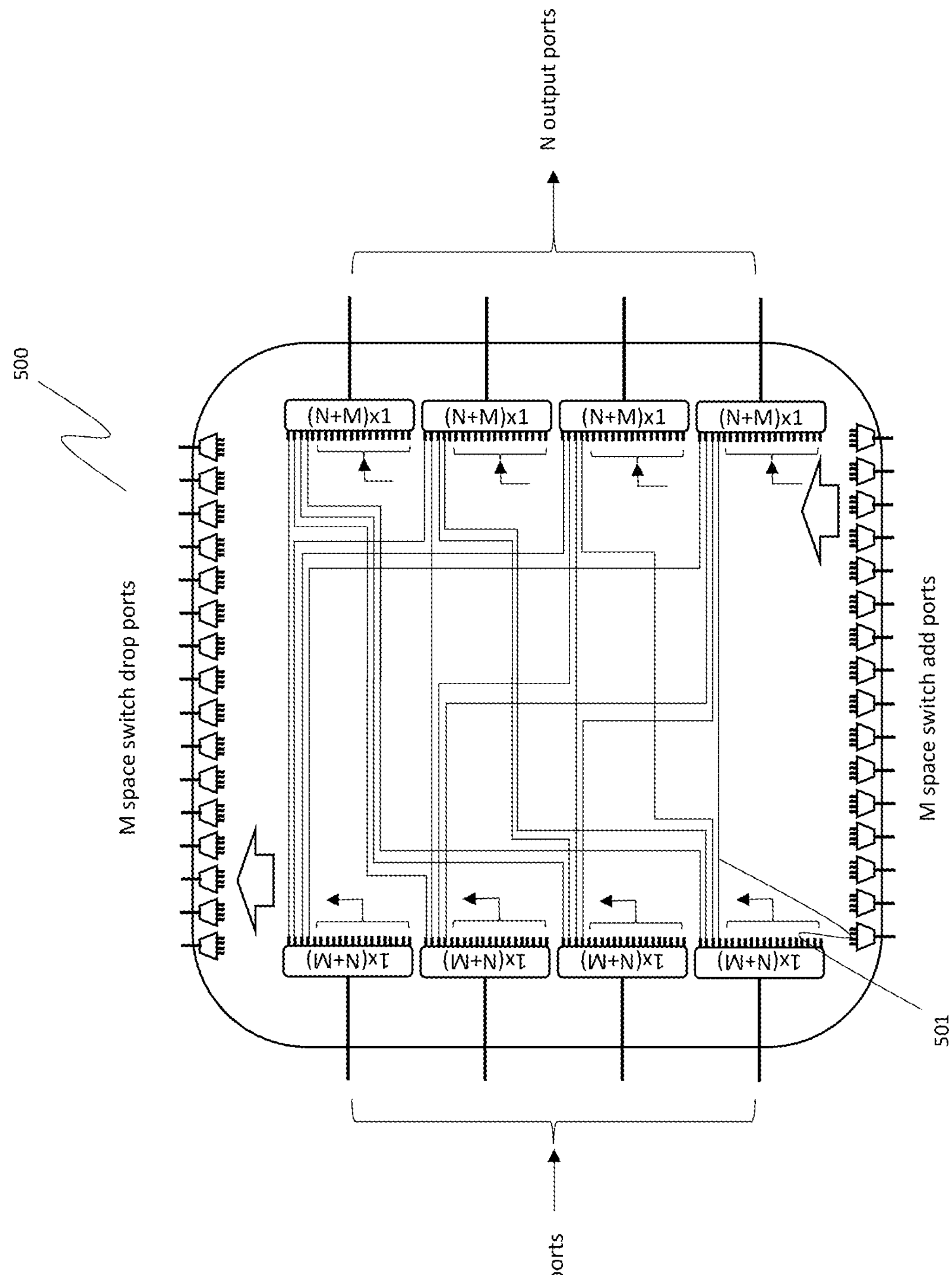
N output ports
500
(N+M)x1
(N+M)x1
(N+M)x1
(N+M)x1
M space switch drop ports
M space switch add ports
1x(N+M)
1x(N+M)
1x(N+M)
1x(N+M)
501
N input ports

FIG. 4

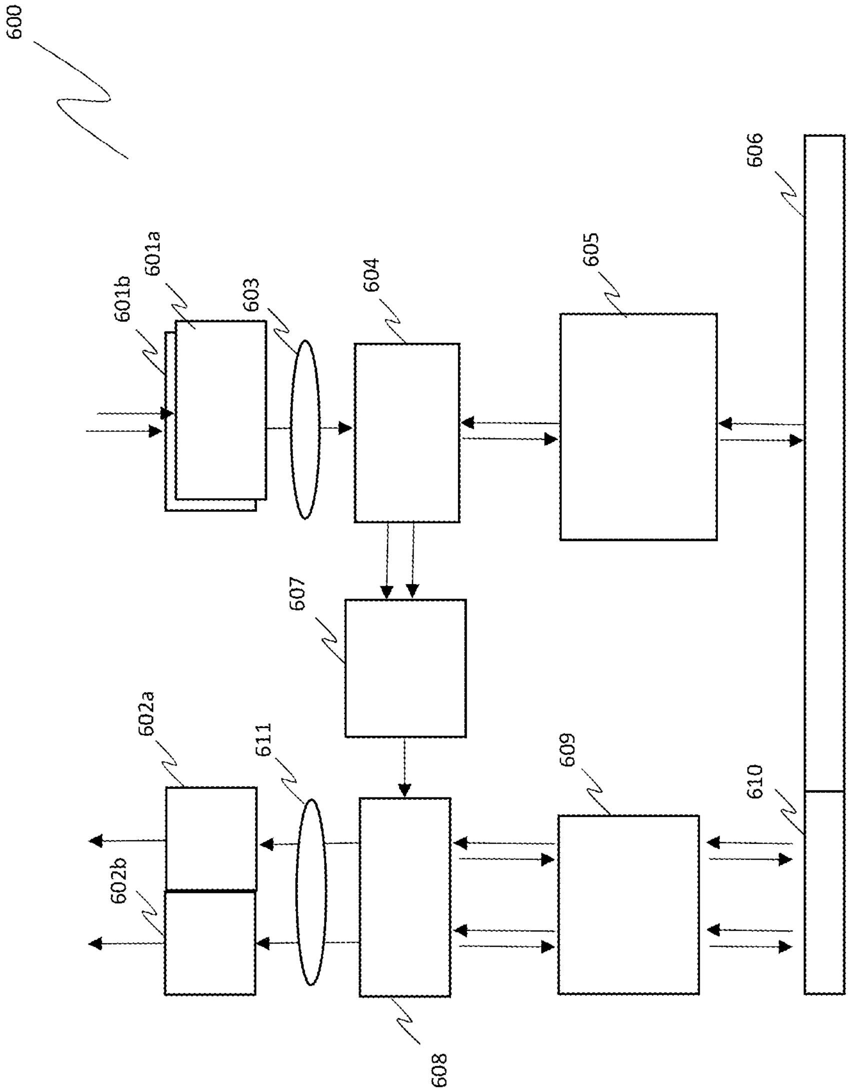

FIG. 5(a)

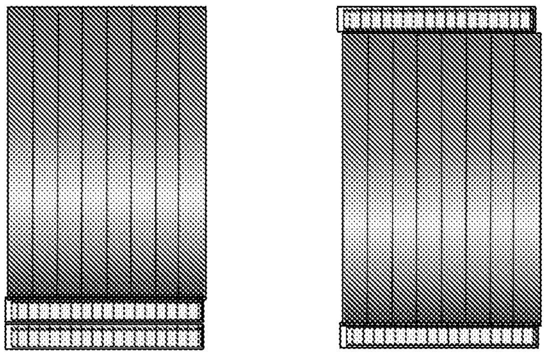

FIG. 5(c)

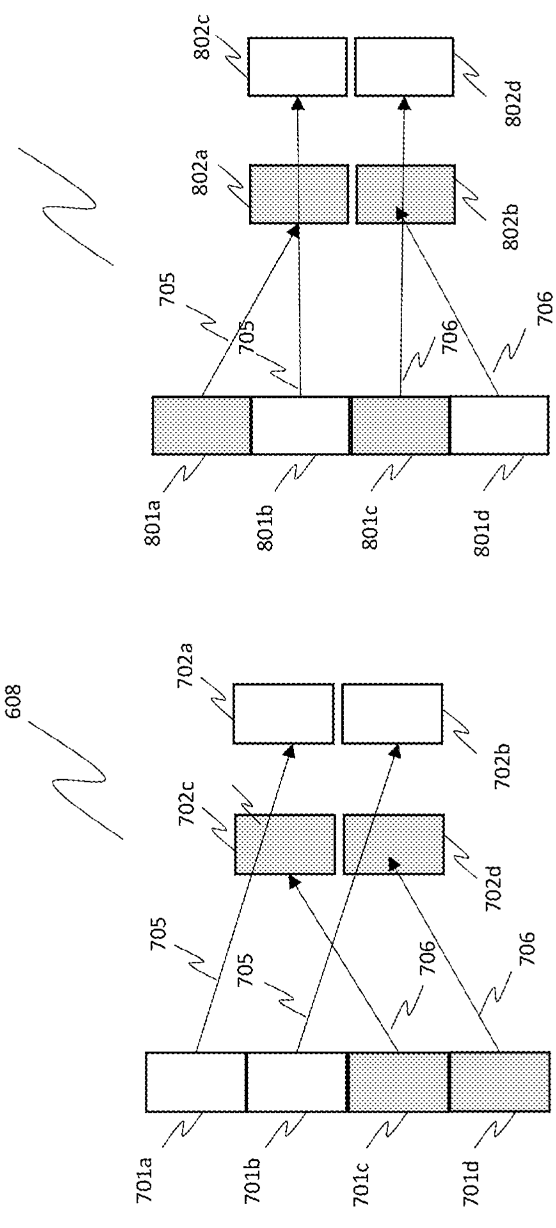
800
802c
802d
802a
802b
705
705
706
706
801a
801b
801c
801d
608
702a
702b
702c
702d
705
705
706
706
701a
701b
701c
701d

FIG. 5(b)

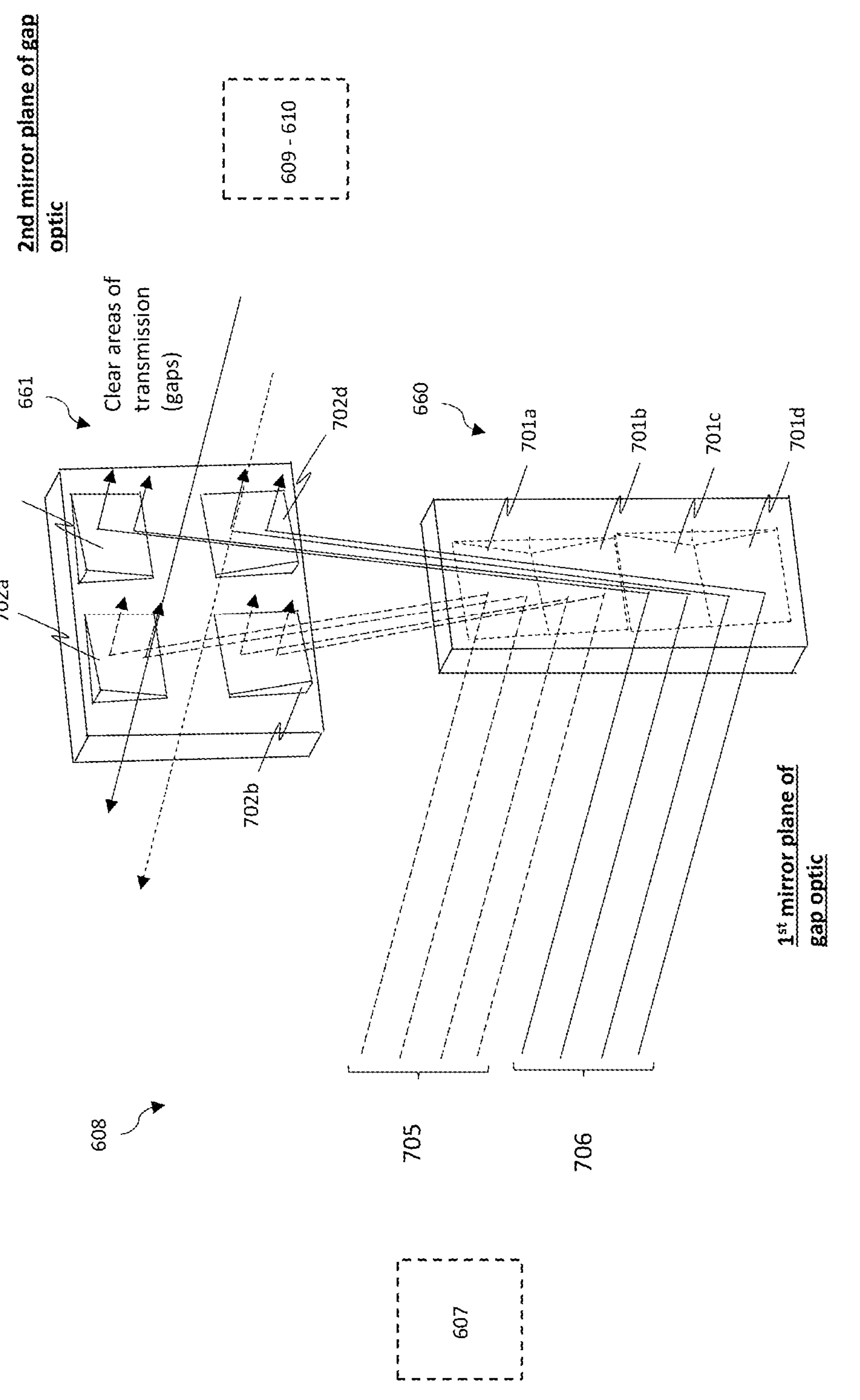
2nd mirror plane of gap optic
609 - 610
Clear areas of transmission (gaps)
661
660
702c
702a
702d
702b
701a
701b
701c
701d
1st mirror plane of gap optic
608
705
706
607

FIG. 6(a)

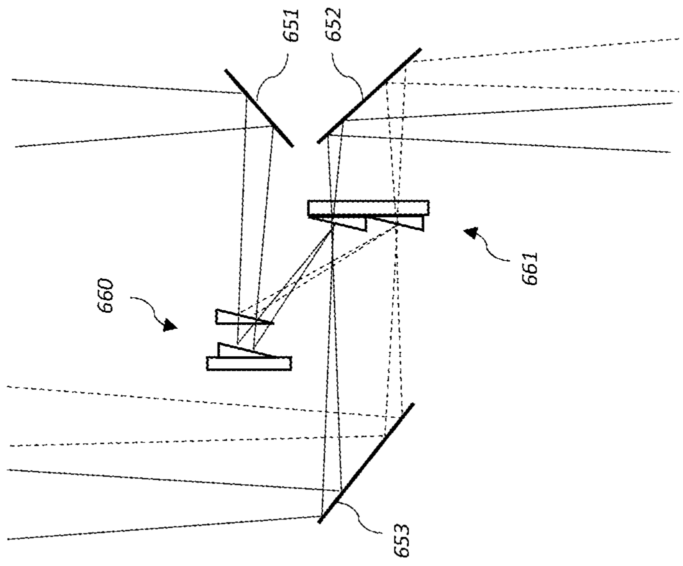
651
652
660
661
653

FIG. 6(b)

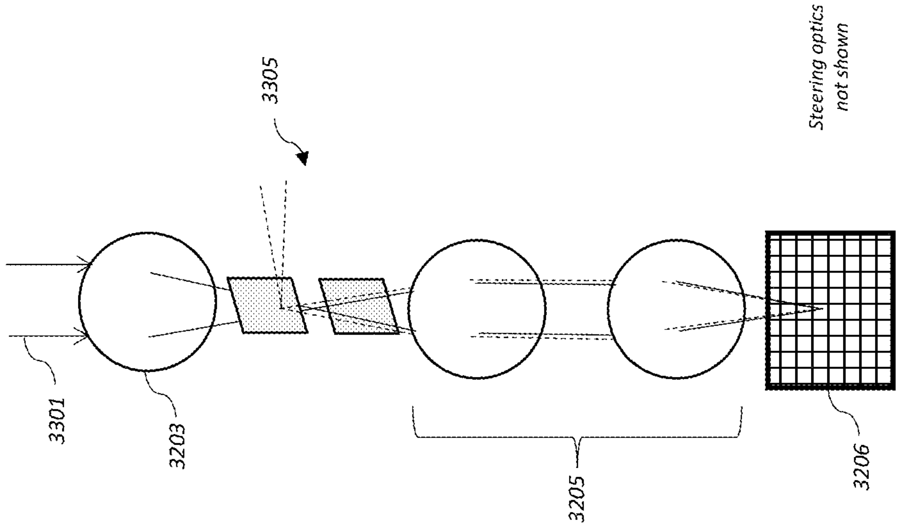
3305
Steering optics not shown
3301
3203
3205
3206

FIG. 7

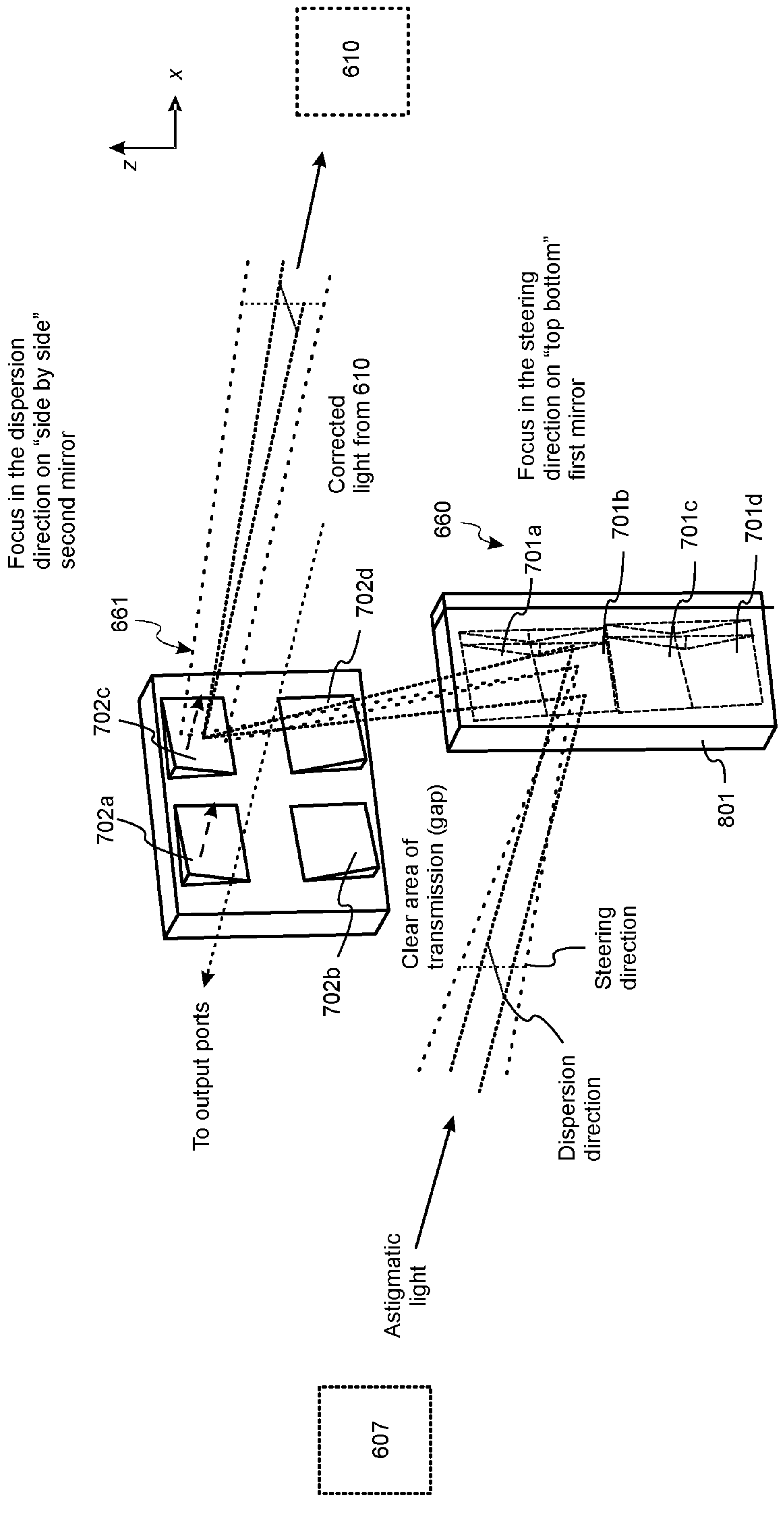
610
x
z
Focus in the dispersion direction on "side by side" second mirror
Corrected light from 610
Focus in the steering direction on "top bottom" first mirror
661
660
701a
701b
701c
701d
702c
702d
702a
702b
801
To output ports
Clear area of transmission (gap)
Steering direction
Dispersion direction
Astigmatic light
607

FIG. 8

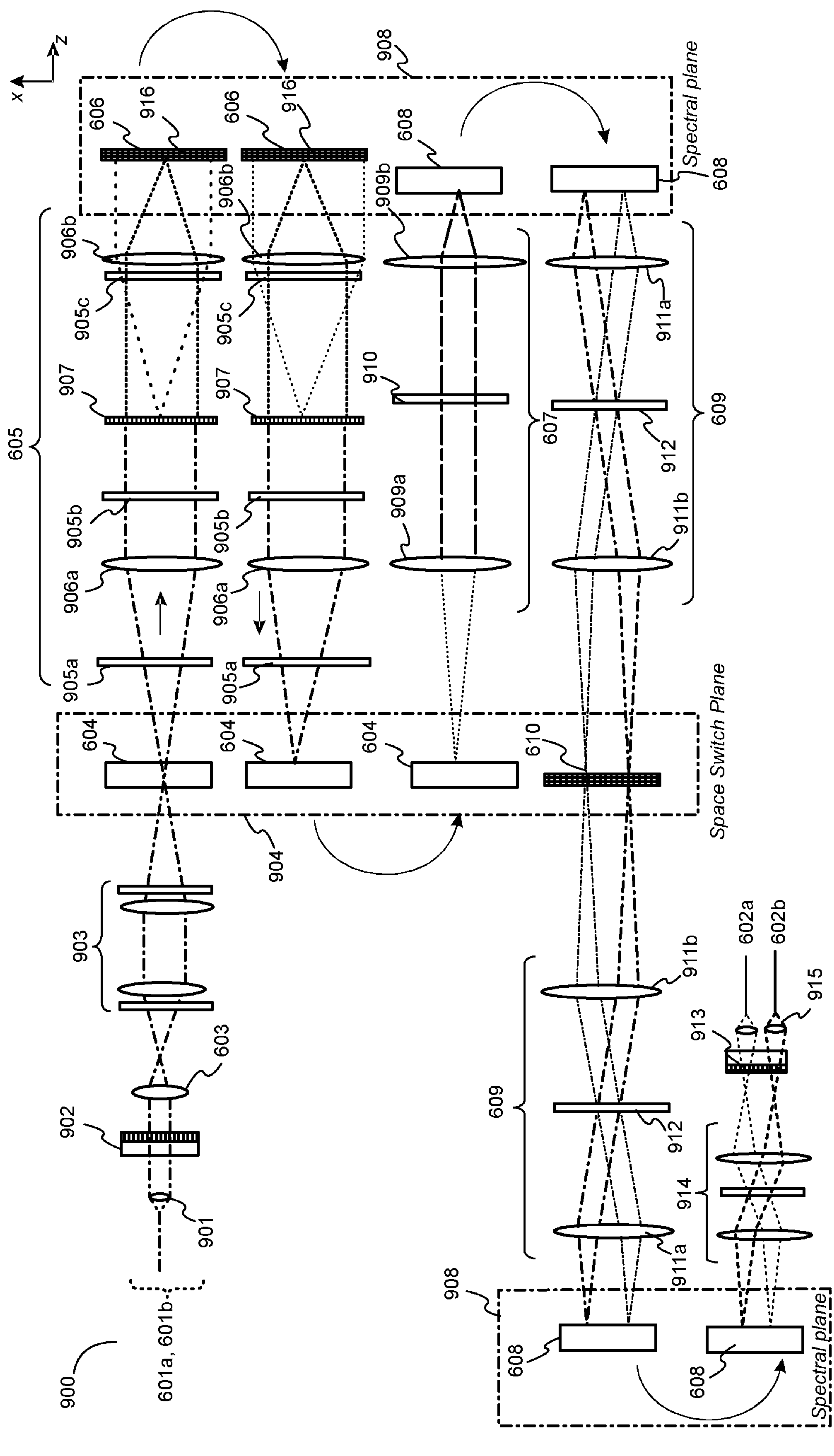
x
z
908
Spectral plane
606
916
606
916
608
608
906b
906b
909b
905c
905c
911a
907
907
910
605
607
912
609
905b
905b
909a
911b
906a
906a
905a
905a
604
604
604
610
Space Switch Plane
904
903
911b
602a
602b
915
913
603
609
912
902
914
901
911a
908
601a, 601b
608
608
900
Spectral plane

FIG. 9(a)

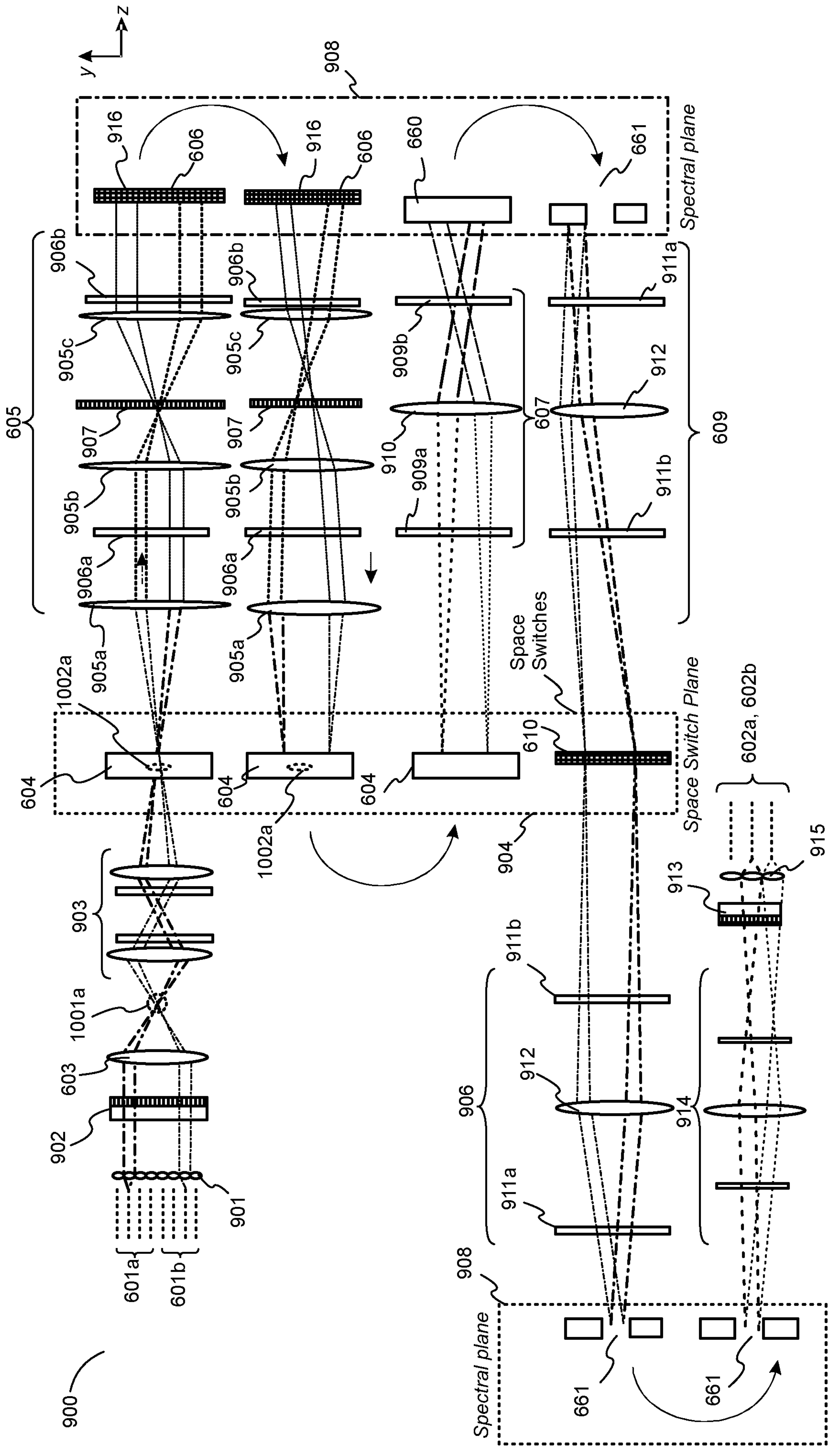
z
y
908
Spectral plane
916
606
916
606
660
661
906b
905c
907
905b
906a
905a
605
906b
905c
907
905b
906a
905a
909b
910
909a
607
911a
912
911b
609
Space Switches
Space Switch Plane
1002a
604
604
1002a
604
610
904
903
1001a
603
902
901
601a
601b
911b
912
911a
906
914
913
915
602a, 602b
908
Spectral plane
661
661
900

FIG. 9(b)

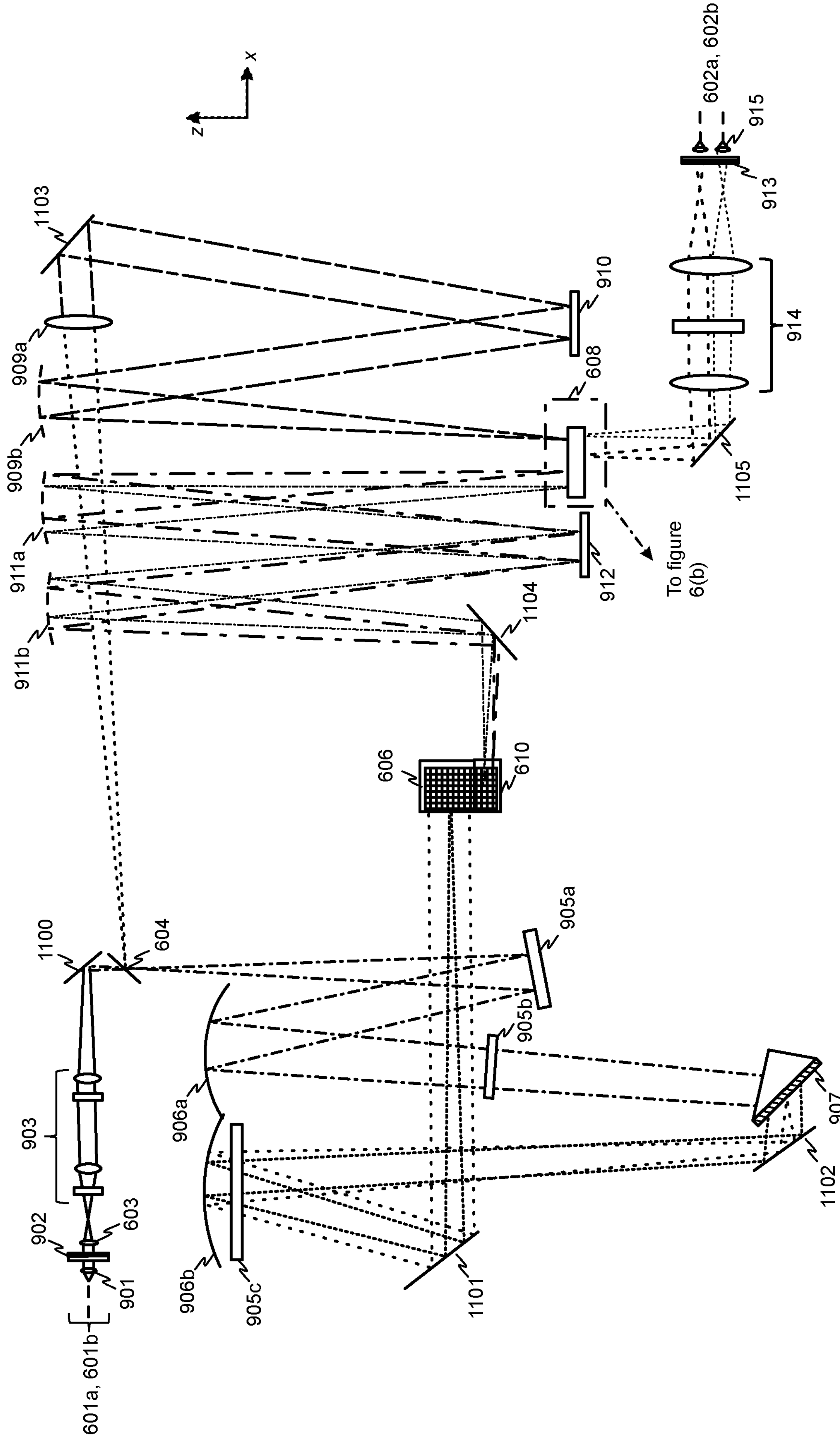
x
z
1103
910
909a
608
909b
914
913
915
602a, 602b
1105
911a
912
To figure 6(b)
911b
1104
606
610
1100
604
905a
905b
903
906a
907
1102
902
603
901
906b
905c
1101
601a, 601b

FIG. 9(c)

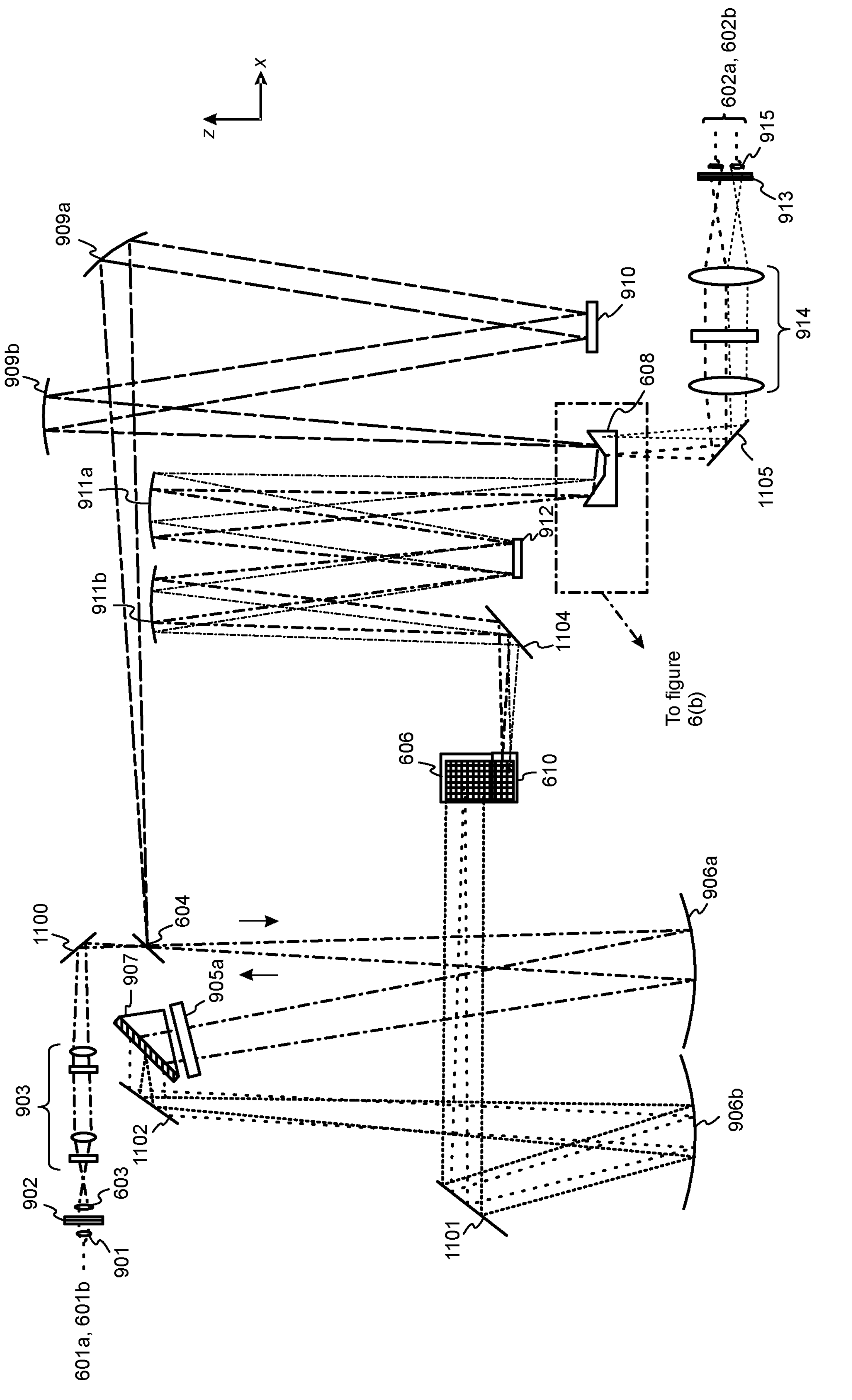
x
z
602a, 602b
915
913
914
909a
910
909b
608
1105
911a
912
911b
1104
To figure 6(b)
606
610
1100
604
906a
907
905a
903
1102
906b
902
603
901
1101
601a, 601b

FIG. 10

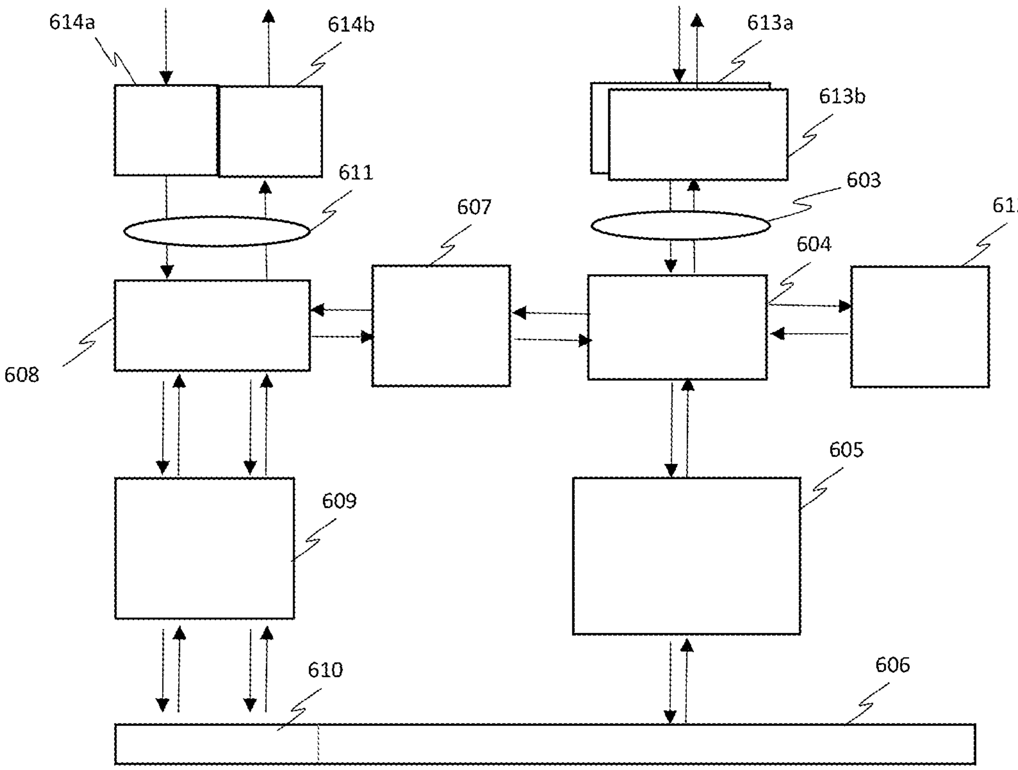

FIG. 11

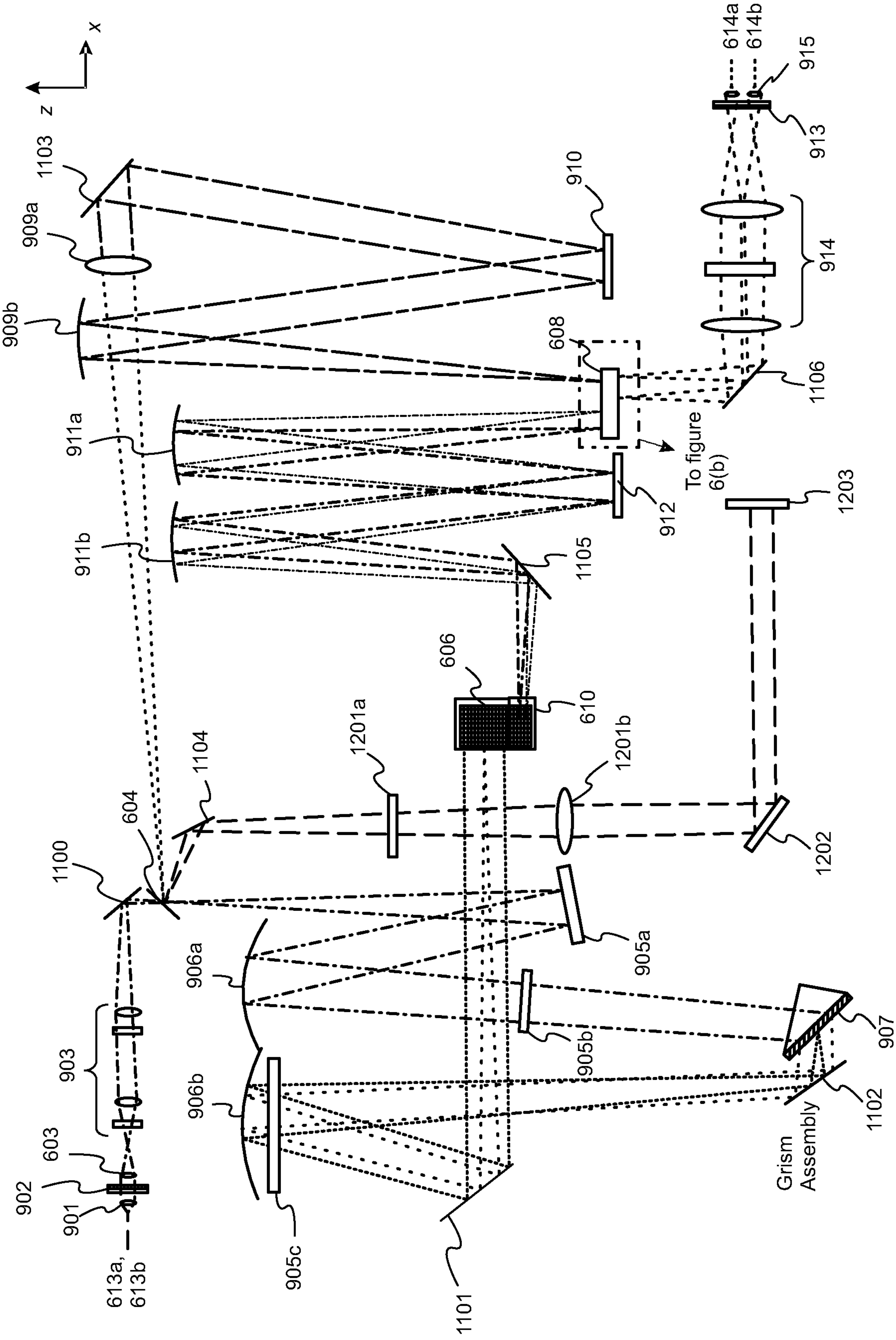
x
z
1103
909a
909b
910
608
911a
911b
912
To figure 6(b)
1105
1106
913
914
915
614a
614b
1203
606
610
1201a
1201b
1104
604
1100
1202
905a
906a
905b
907
903
603
902
901
613a, 613b
906b
905c
1101
1102
Grism Assembly

FIG. 12(a)

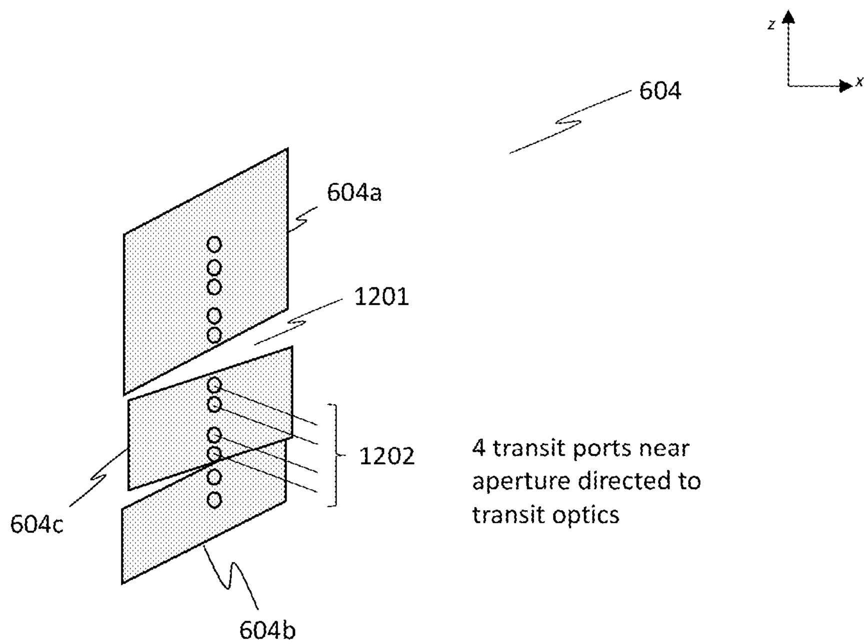
z
x
604
604a
1201
1202
4 transit ports near aperture directed to transit optics
604c
604b

FIG. 12(b)

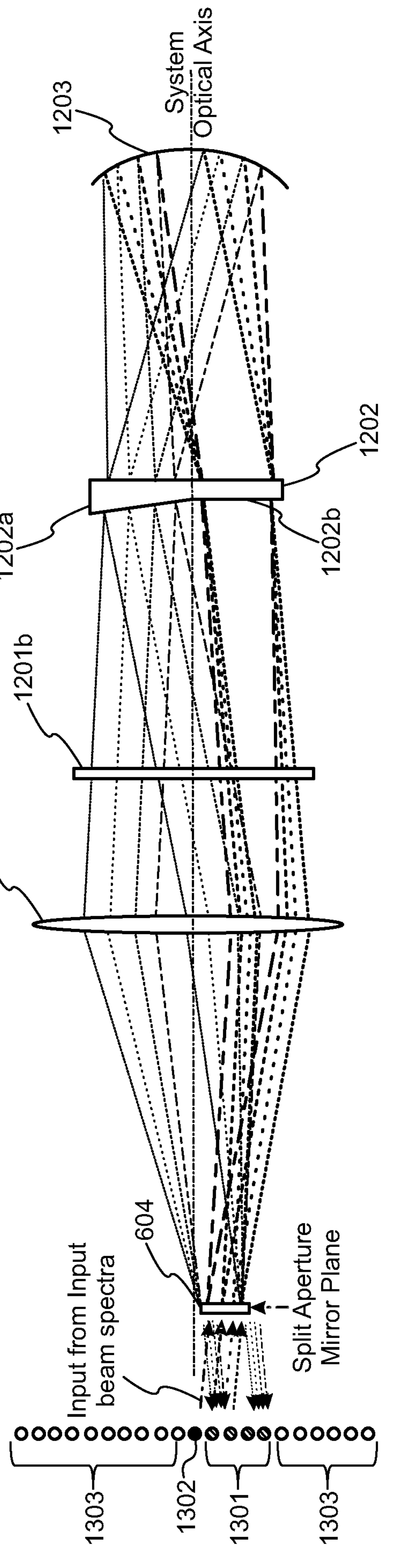
System
Optical Axis
1203
1202
1202a
1202b
1201b
1201a
604
Input from Input
beam spectra
Split Aperture
Mirror Plane
1303
1302
1301
1303

FIG. 13(a)

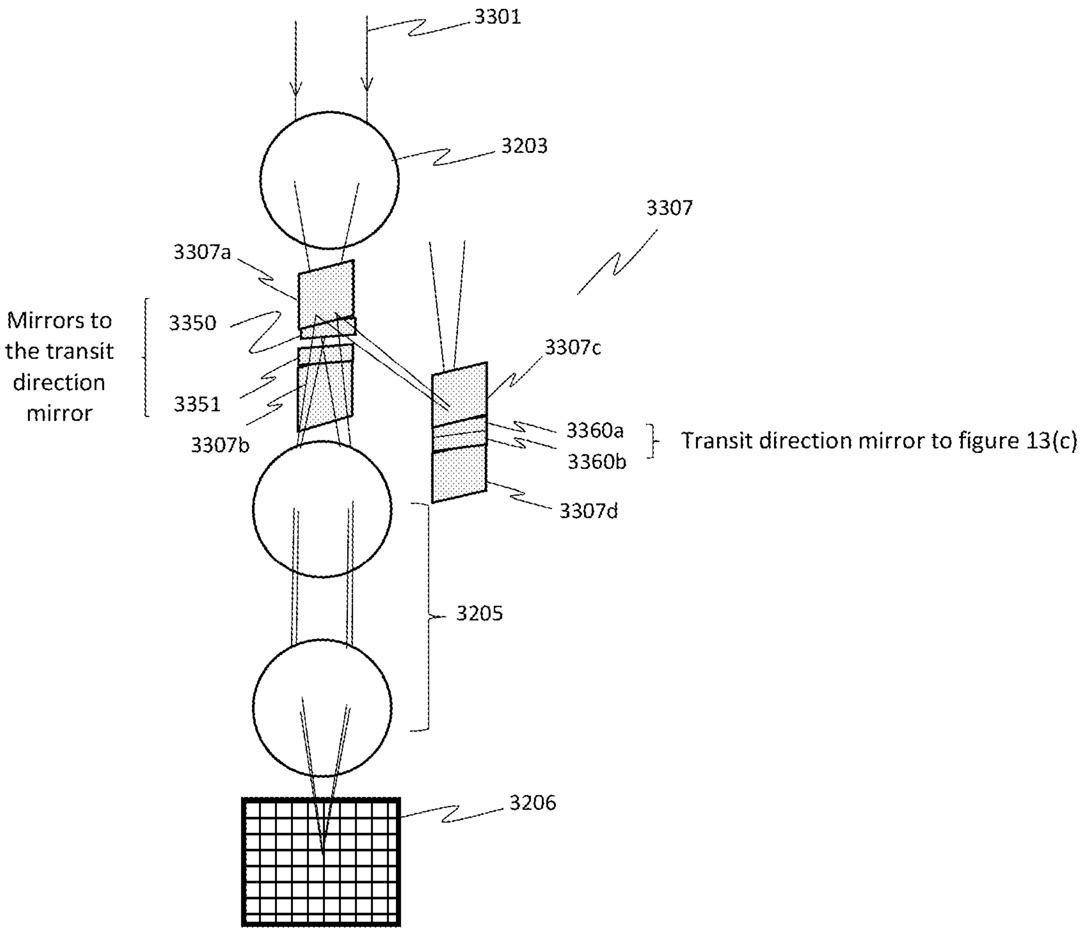
3301
3203
3307
3307a
Mirrors to the transit direction mirror
3350
3351
3307b
3307c
3360a
3360b
Transit direction mirror to figure 13(c)
3307d
3205
3206

FIG. 13(b)

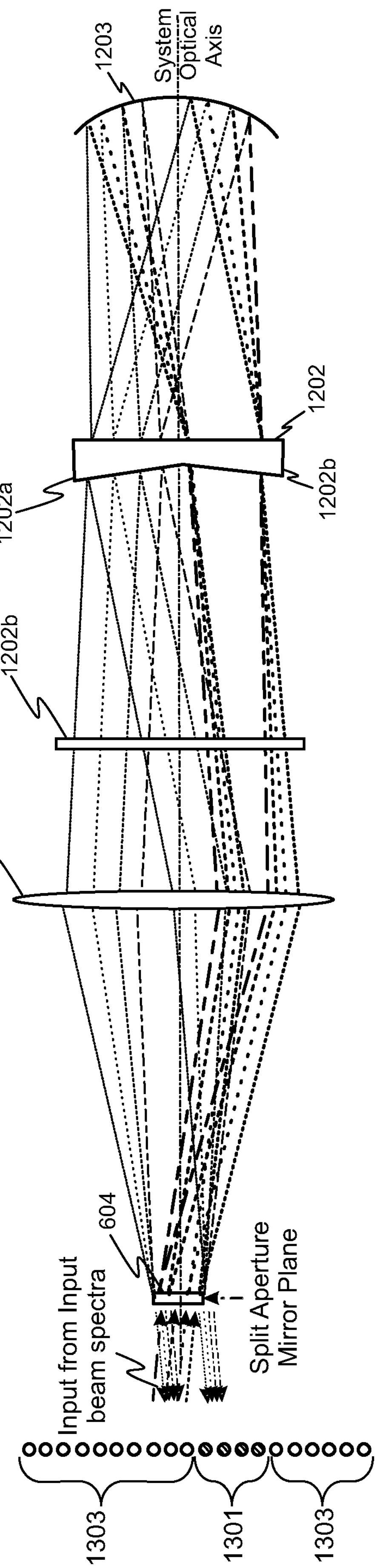
1203
System Optical Axis
1202
1202b
1202a
1202b
1202a
604
Split Aperture Mirror Plane
Input from Input beam spectra
1303
1301
1303

FIG. 13(c)

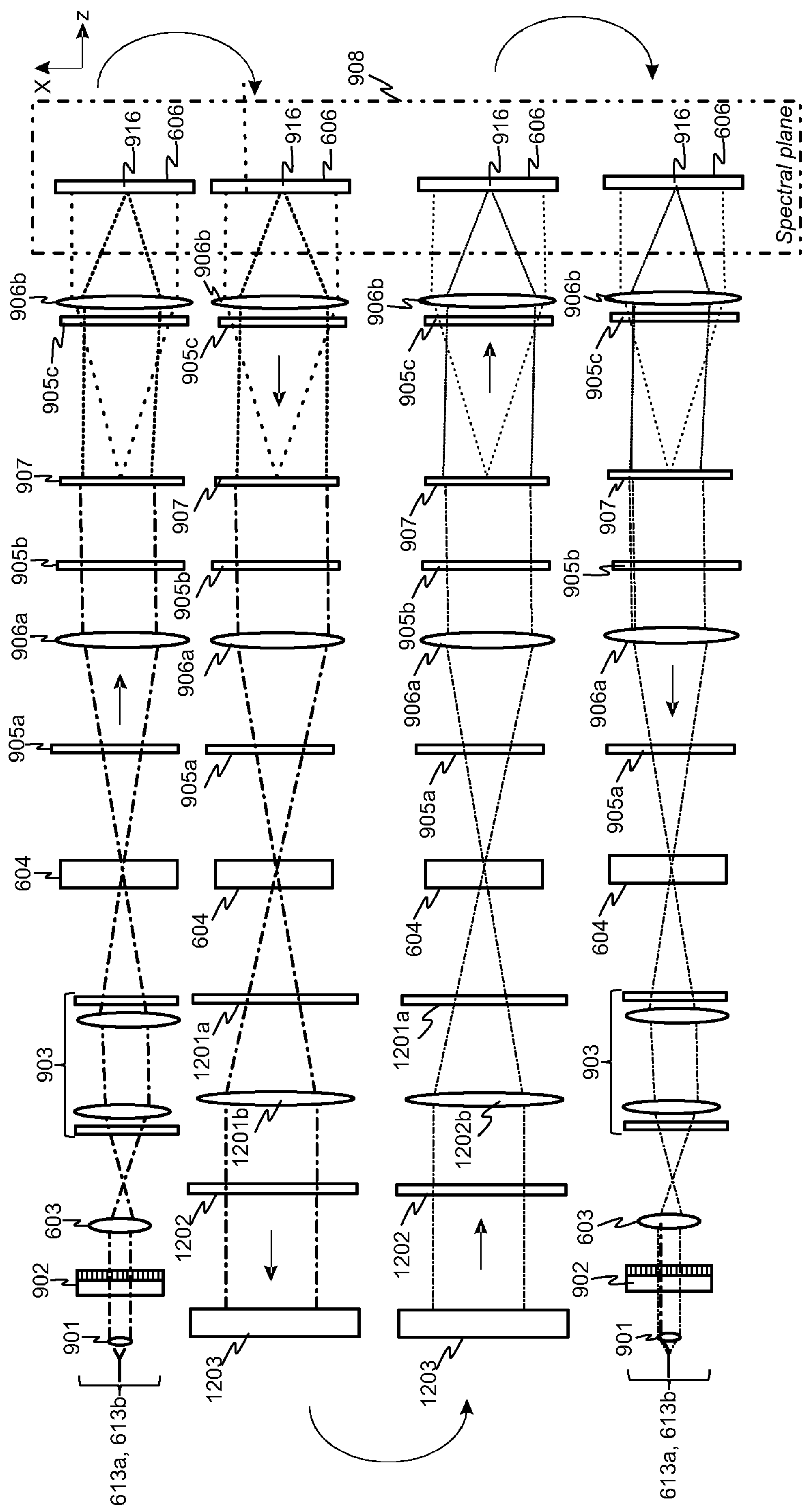
Z
X
908
Spectral plane
916
606
906b
905c
907
905b
906a
905a
604
903
603
902
901
613a, 613b
1201a
1201b
1202
1202b
1203

FIG. 14(a)

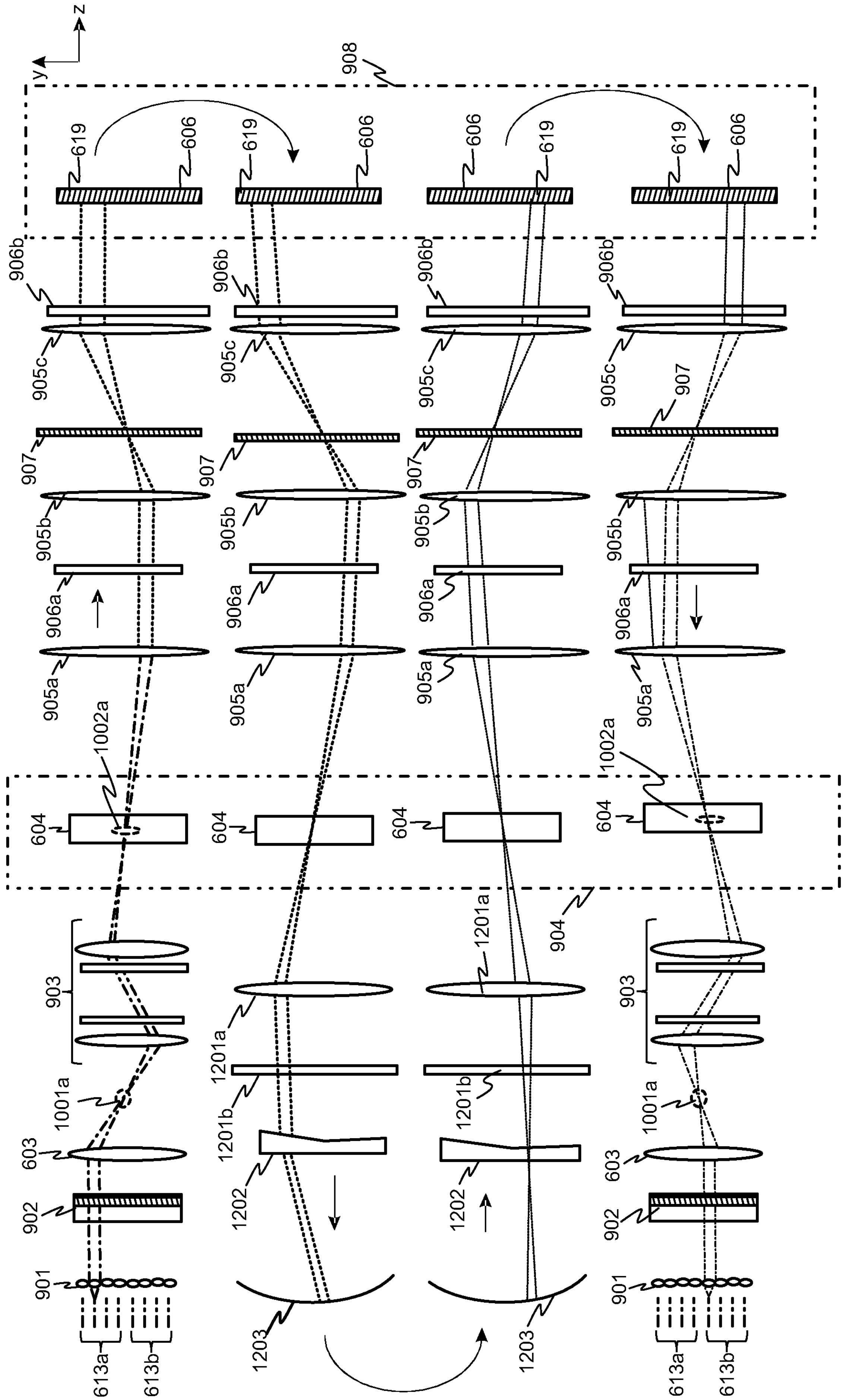
z
y
908
619
606
906b
905c
907
905b
906a
905a
1002a
604
904
903
1201a
1201b
1202
1001a
603
902
901
1203
613a
613b

FIG. 14(b)

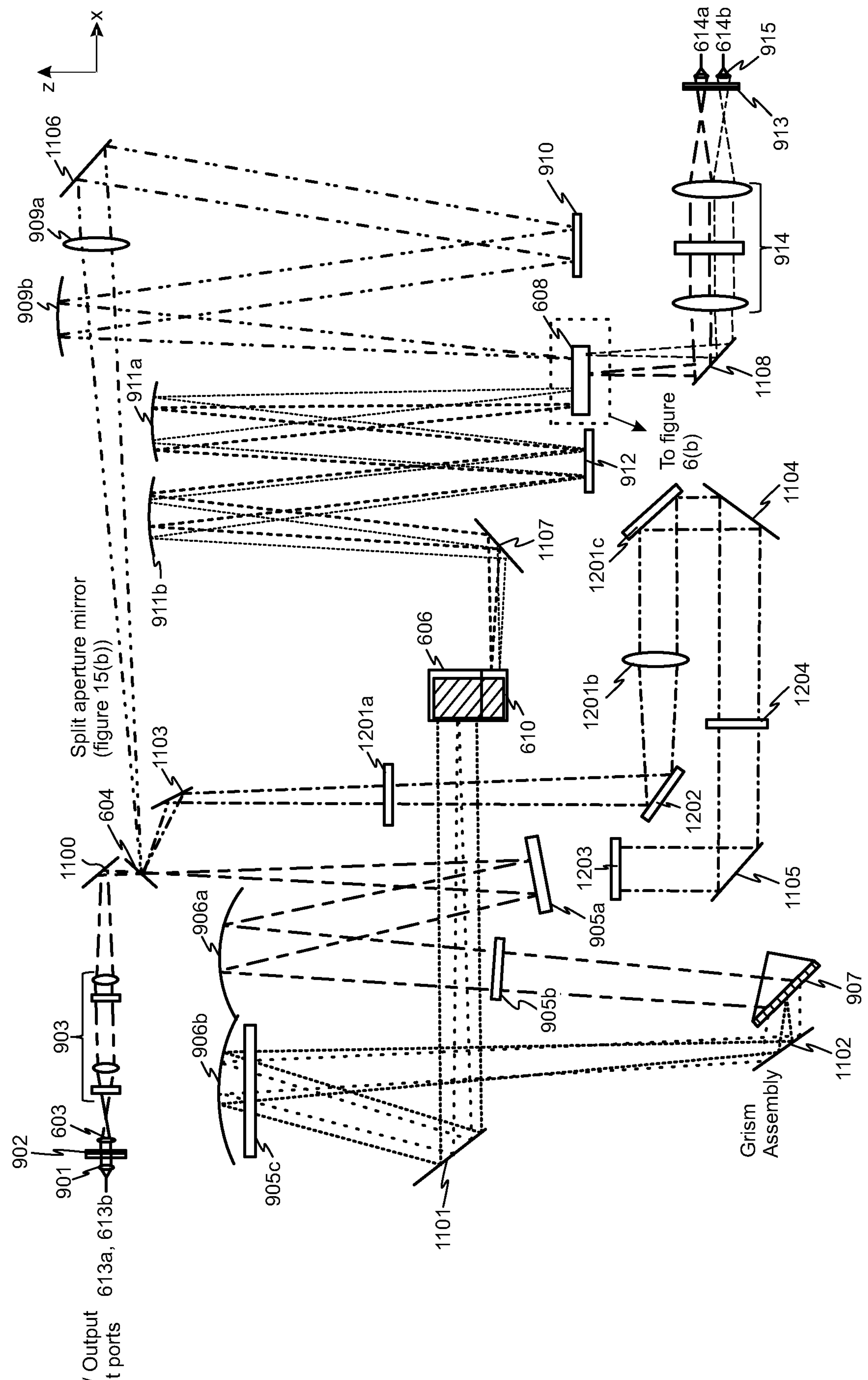
x
z
1106
909a
909b
910
608
911a
To figure 6(b)
912
1108
914
913
915
614a
614b
1104
1201c
1107
911b
Split aperture mirror (figure 15(b))
1103
604
1100
606
610
1201a
1201b
1204
1202
1203
1105
905a
906a
905b
907
903
906b
1102
Grism Assembly
905c
902
603
901
613a, 613b
1101
Input/ Output transit ports

FIG. 15(a)

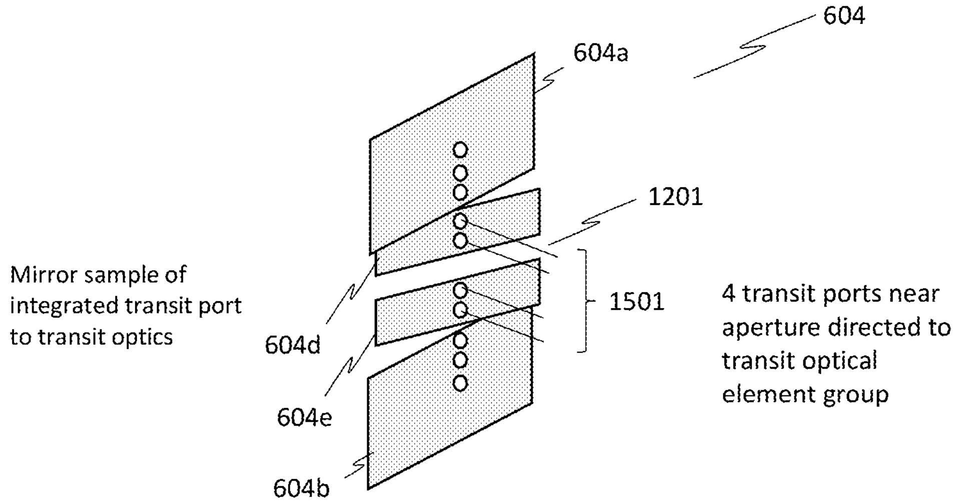
604
604a
1201
Mirror sample of
integrated transit port
to transit optics
604d
1501
4 transit ports near
aperture directed to
transit optical
element group
604e
604b

FIG. 15(b)

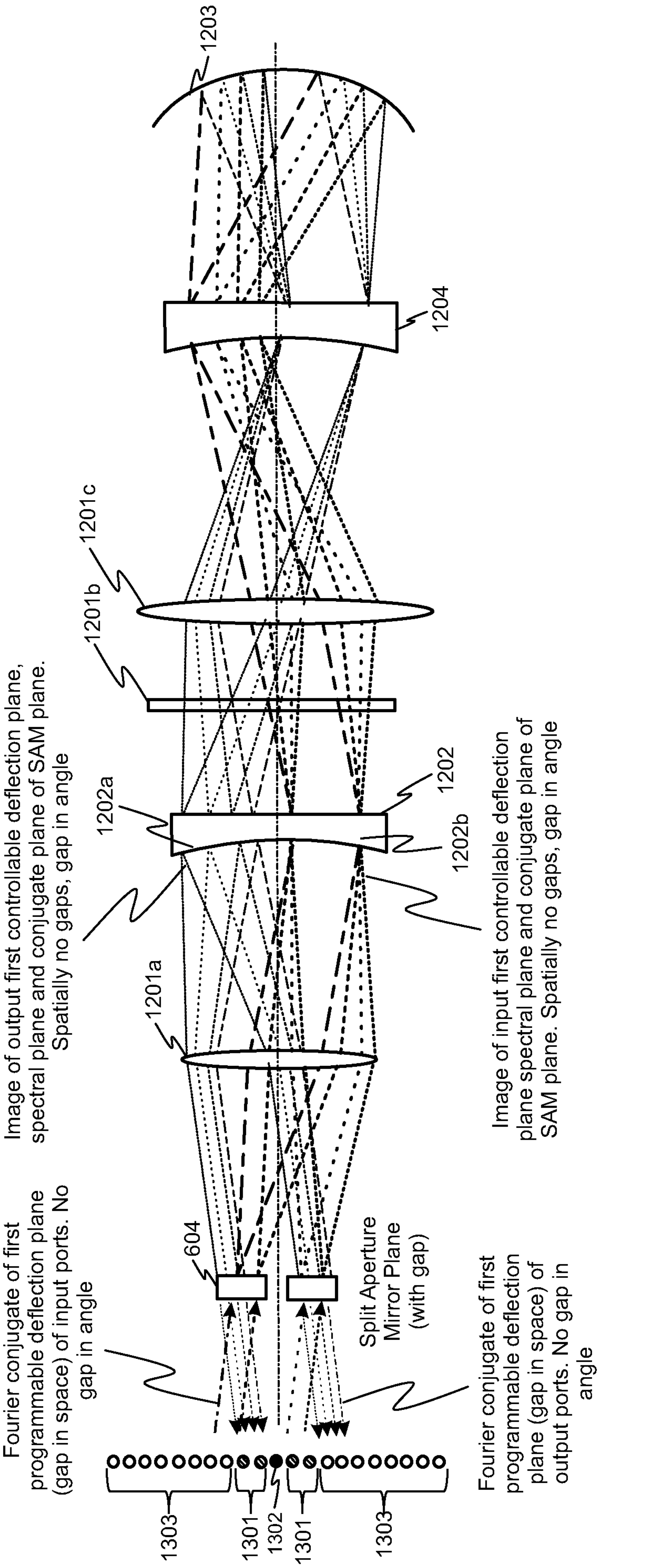
1203
1204
1201c
1201b
Image of output first controllable deflection plane, spectral plane and conjugate plane of SAM plane. Spatially no gaps, gap in angle
1202a
1202
1202b
1201a
Image of input first controllable deflection plane spectral plane and conjugate plane of SAM plane. Spatially no gaps, gap in angle
604
Fourier conjugate of first programmable deflection plane (gap in space) of input ports. No gap in angle
Split Aperture Mirror Plane (with gap)
Fourier conjugate of first programmable deflection plane (gap in space) of output ports. No gap in angle
1303
1301
1302
1301
1303

FIG. 16(a)

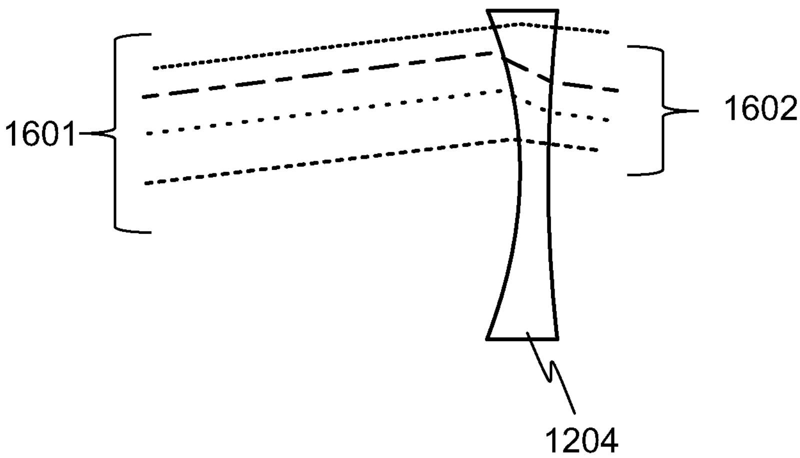

FIG. 16(b)

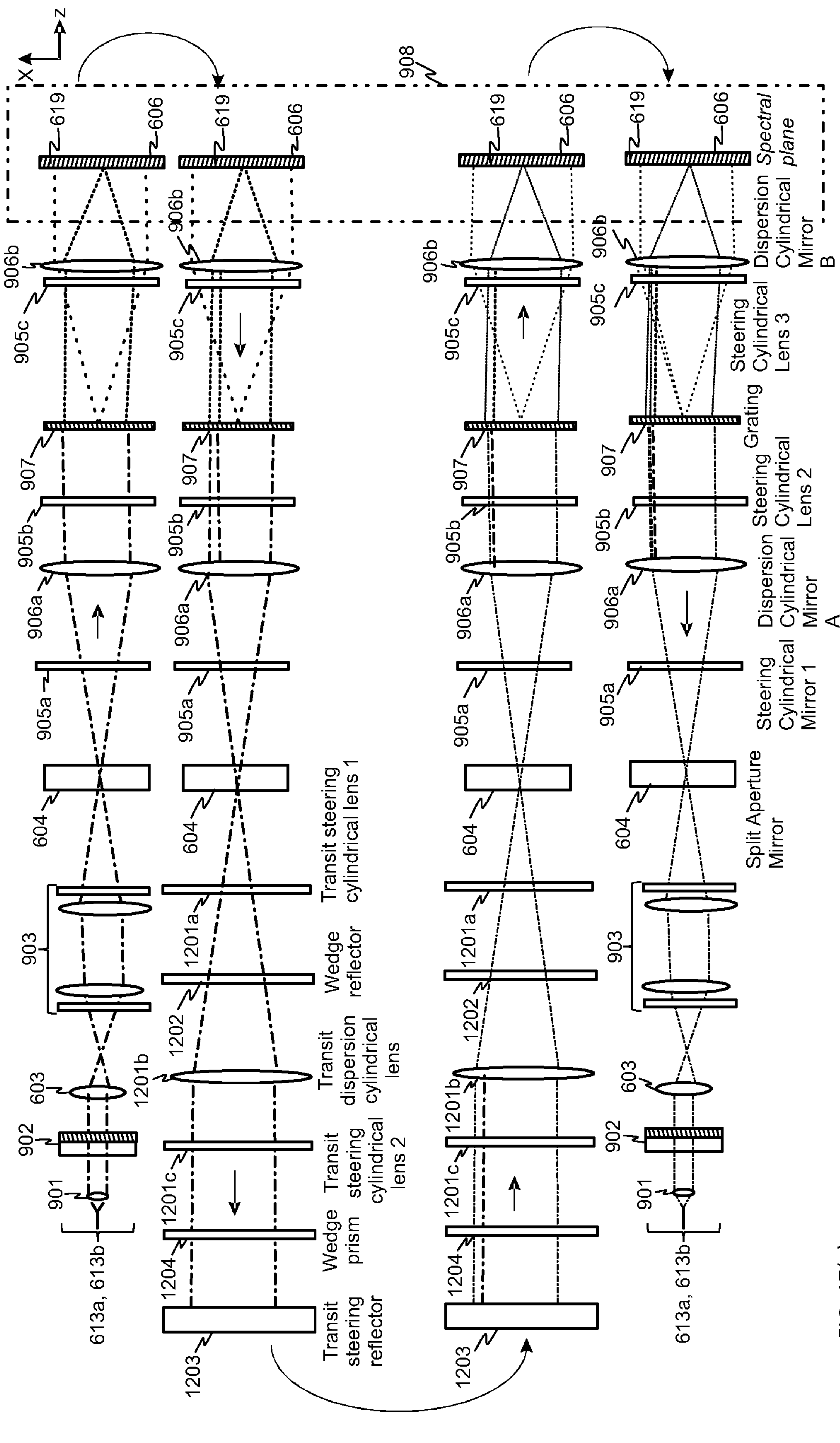
X
Z
908
619
606
906b
905c
907
905b
906a
905a
604
903
603
902
901
613a, 613b
1201a
1202
1201b
1201c
1204
1203
Transit steering cylindrical lens 1
Wedge reflector
Transit dispersion cylindrical lens
Transit steering cylindrical lens 2
Wedge prism
Transit steering reflector
Spectral plane
Dispersion Cylindrical Mirror B
Steering Cylindrical Lens 3
Grating
Steering Cylindrical Lens 2
Dispersion Cylindrical Mirror A
Steering Cylindrical Mirror 1
Split Aperture Mirror

FIG. 17(a)

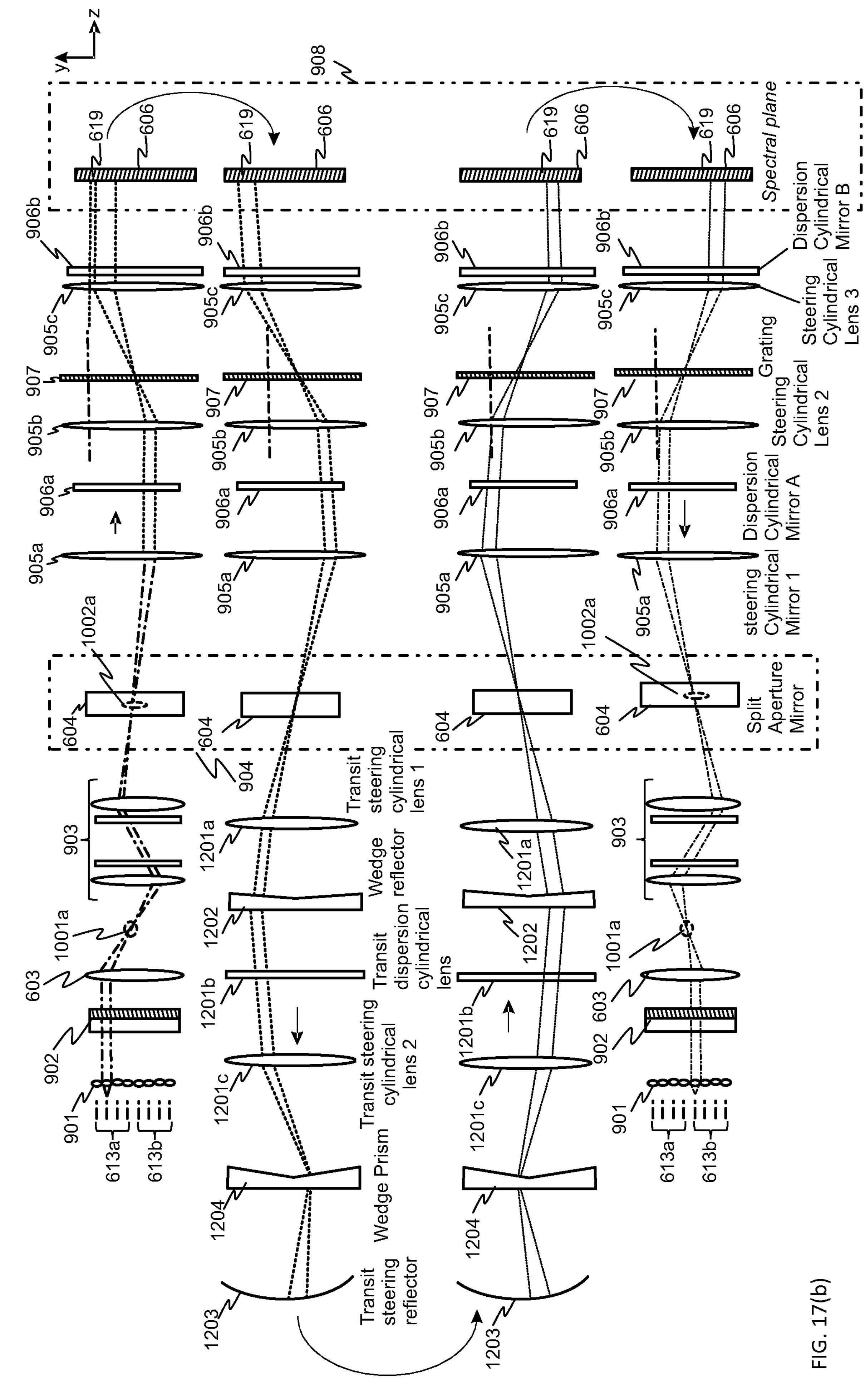
z
y
908
Spectral plane
619
606
906b
905c
907
905b
906a
905a
1002a
604
904
903
1001a
603
902
901
613a
613b
1201a
1202
1201b
1201c
1204
1203
Dispersion Cylindrical Mirror B
Steering Cylindrical Lens 3
Grating
Steering Cylindrical Lens 2
Dispersion Cylindrical Mirror A
steering Cylindrical Mirror 1
Split Aperture Mirror
Transit steering cylindrical lens 1
Wedge reflector
Transit dispersion cylindrical lens
Transit steering cylindrical lens 2
Wedge Prism
Transit steering reflector

FIG. 17(b)

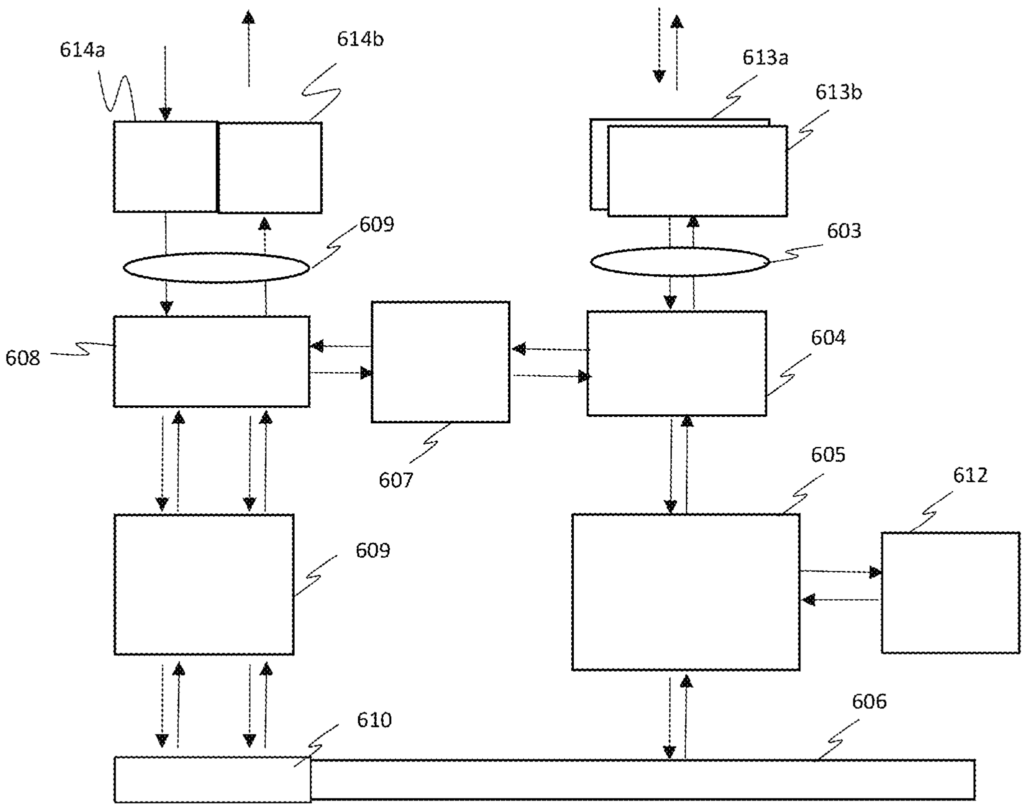

FIG. 18

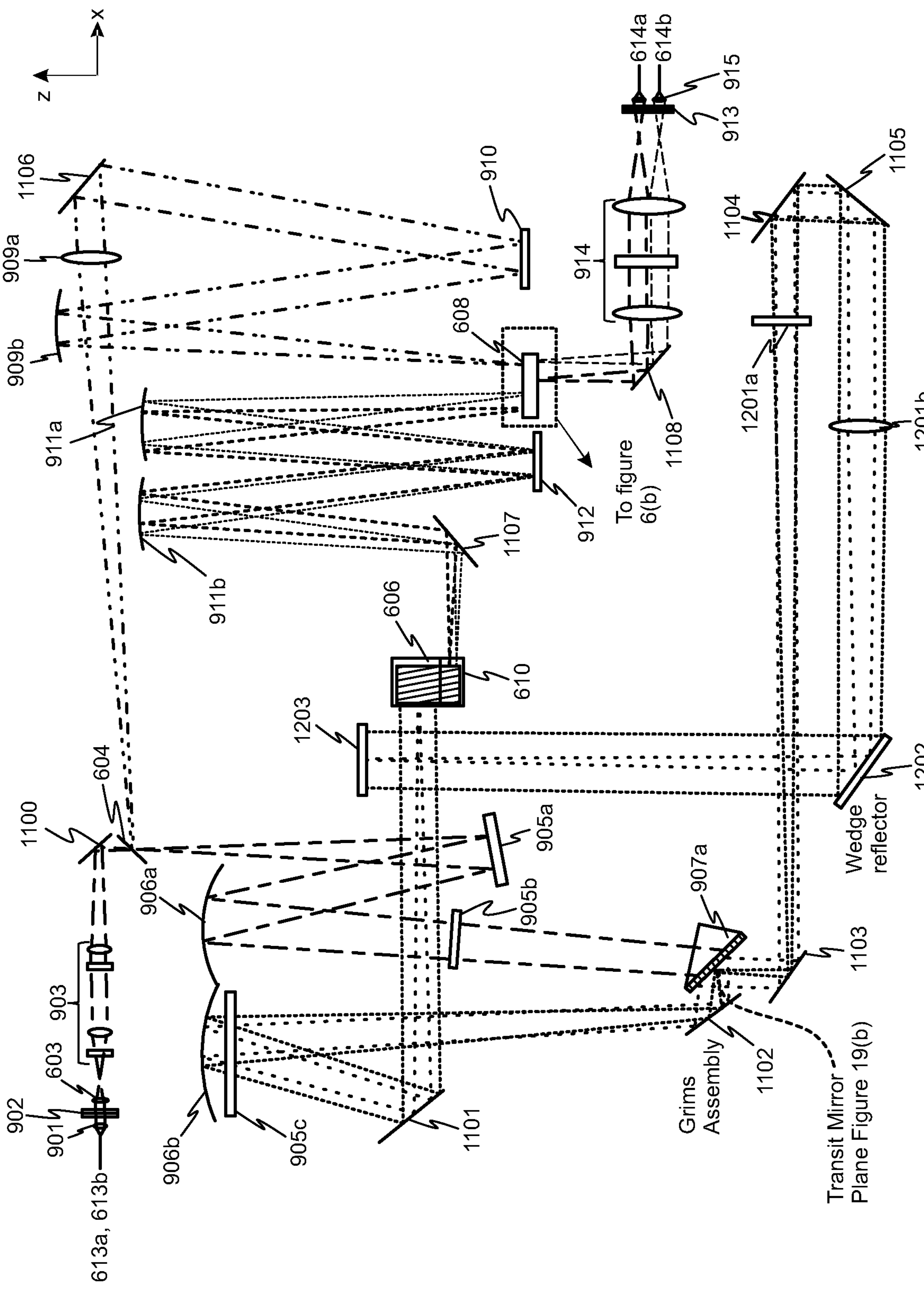
z
x
1106
909a
909b
910
608
914
913
915
614a
614b
911a
1108
To figure 6(b)
912
1107
911b
606
610
1203
1104
1105
1201a
1201b
1100
604
906a
905a
905b
903
603
902
901
613a, 613b
906b
905c
1101
907a
Grims Assembly
1102
1103
1202
Wedge reflector
Transit Mirror Plane Figure 19(b)

FIG. 19(a)

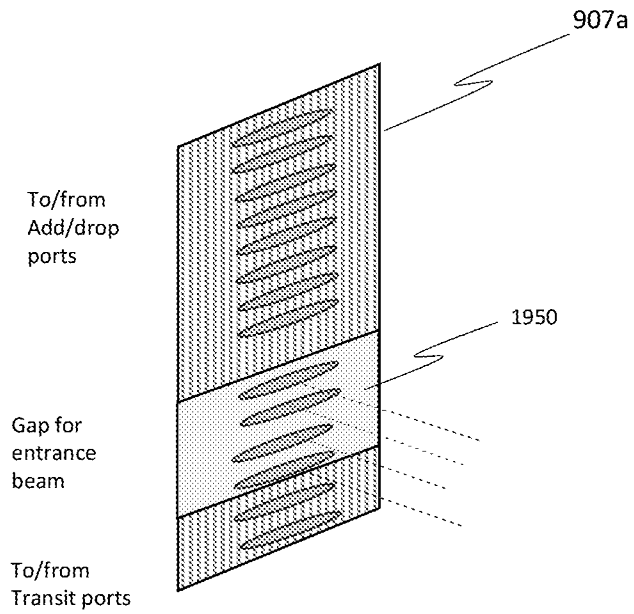
907a
To/from
Add/drop
ports
1950
Gap for
entrance
beam
To/from
Transit ports

FIG. 19(b)

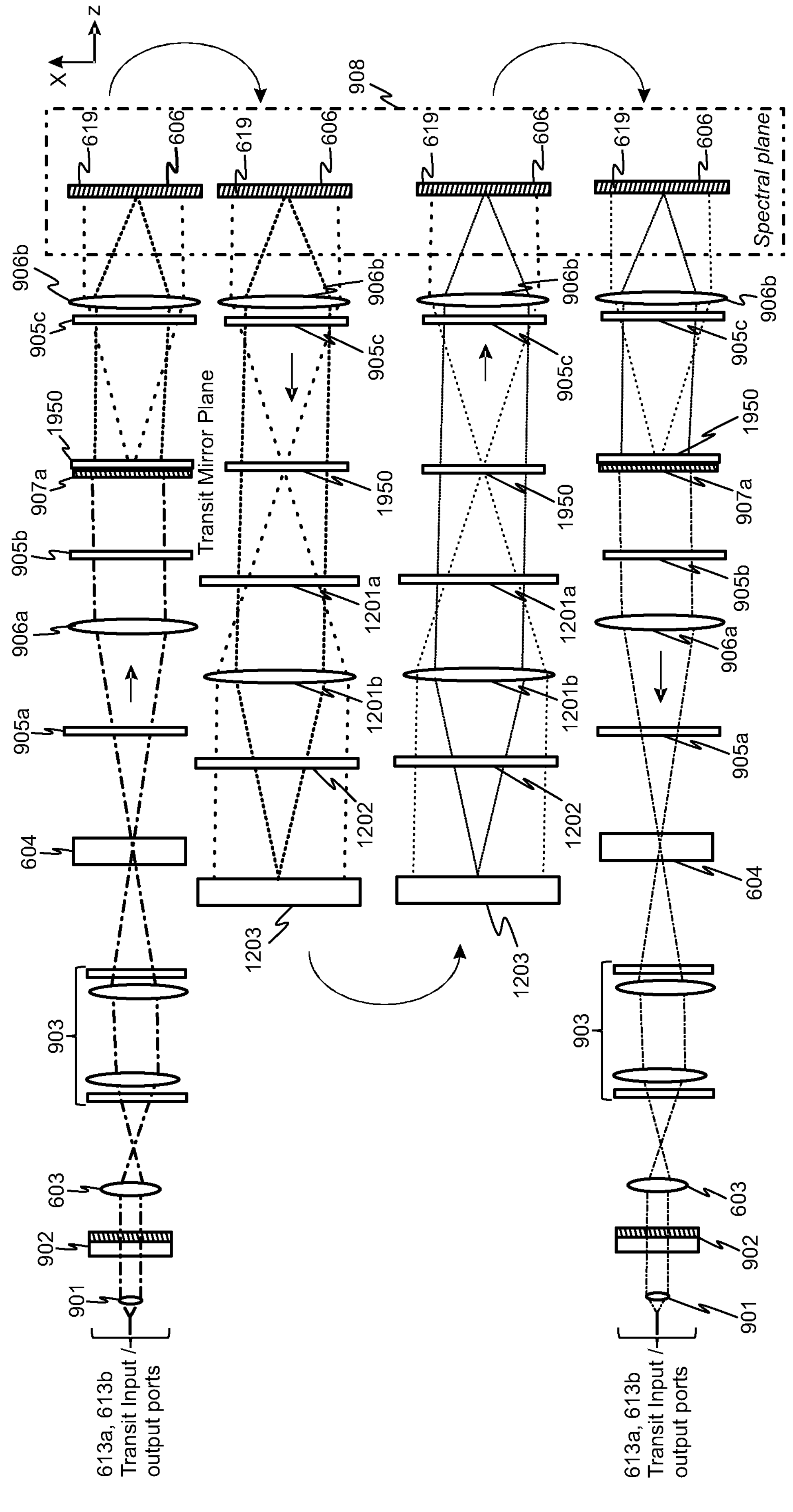
z
X
908
Spectral plane
619
606
906b
905c
1950
907a
905b
906a
905a
604
903
603
902
901
613a, 613b
Transit Input /
output ports
Transit Mirror Plane
1201a
1201b
1202
1203

FIG. 19(c)

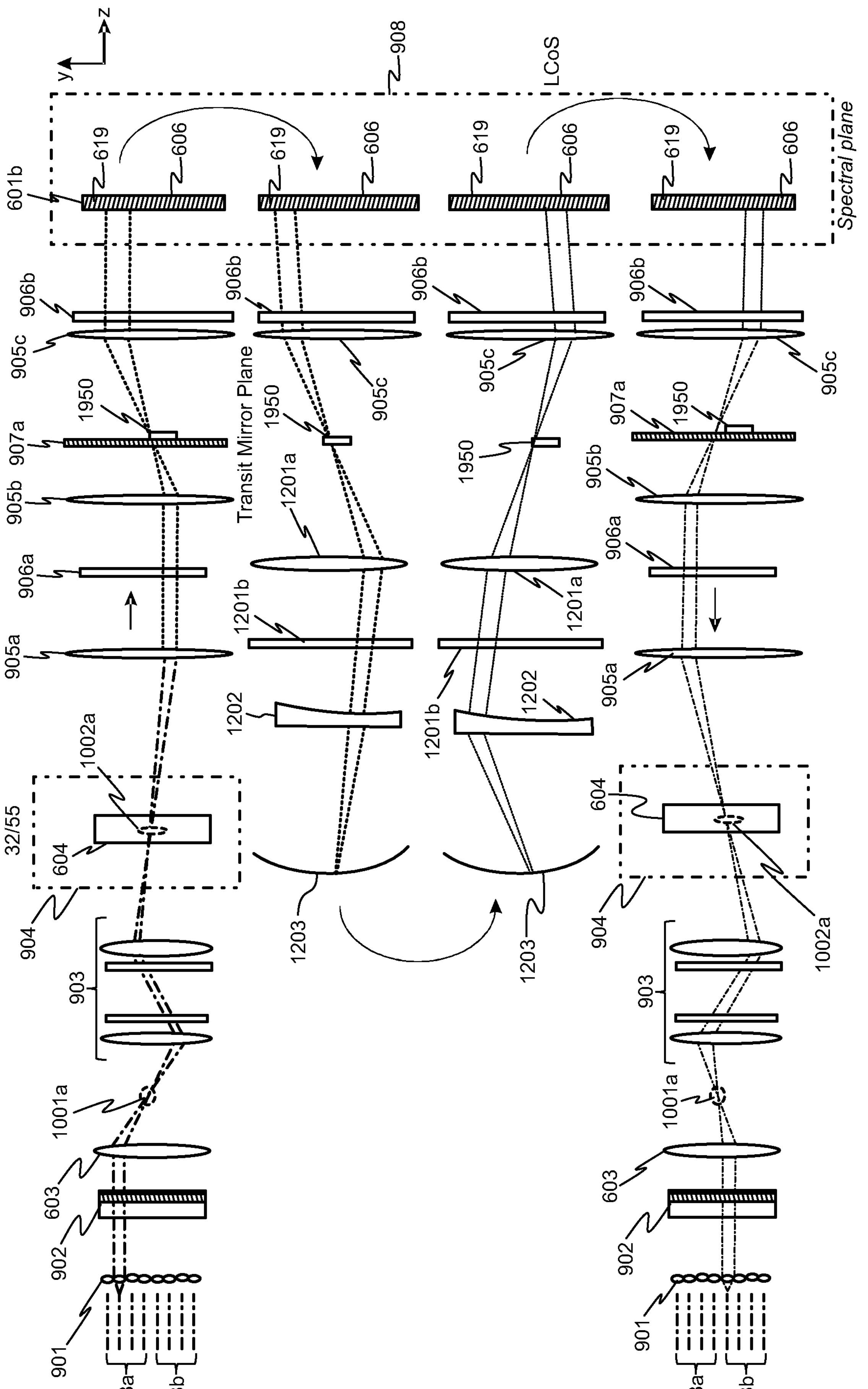
y
z
908
LCoS
Spectral plane
601b
619
606
906b
905c
1950
907a
905b
906a
905a
Transit Mirror Plane
1201a
1201b
1202
1203
1002a
32/55
604
904
903
1001a
603
902
901
613a
613b

FIG. 19(d)

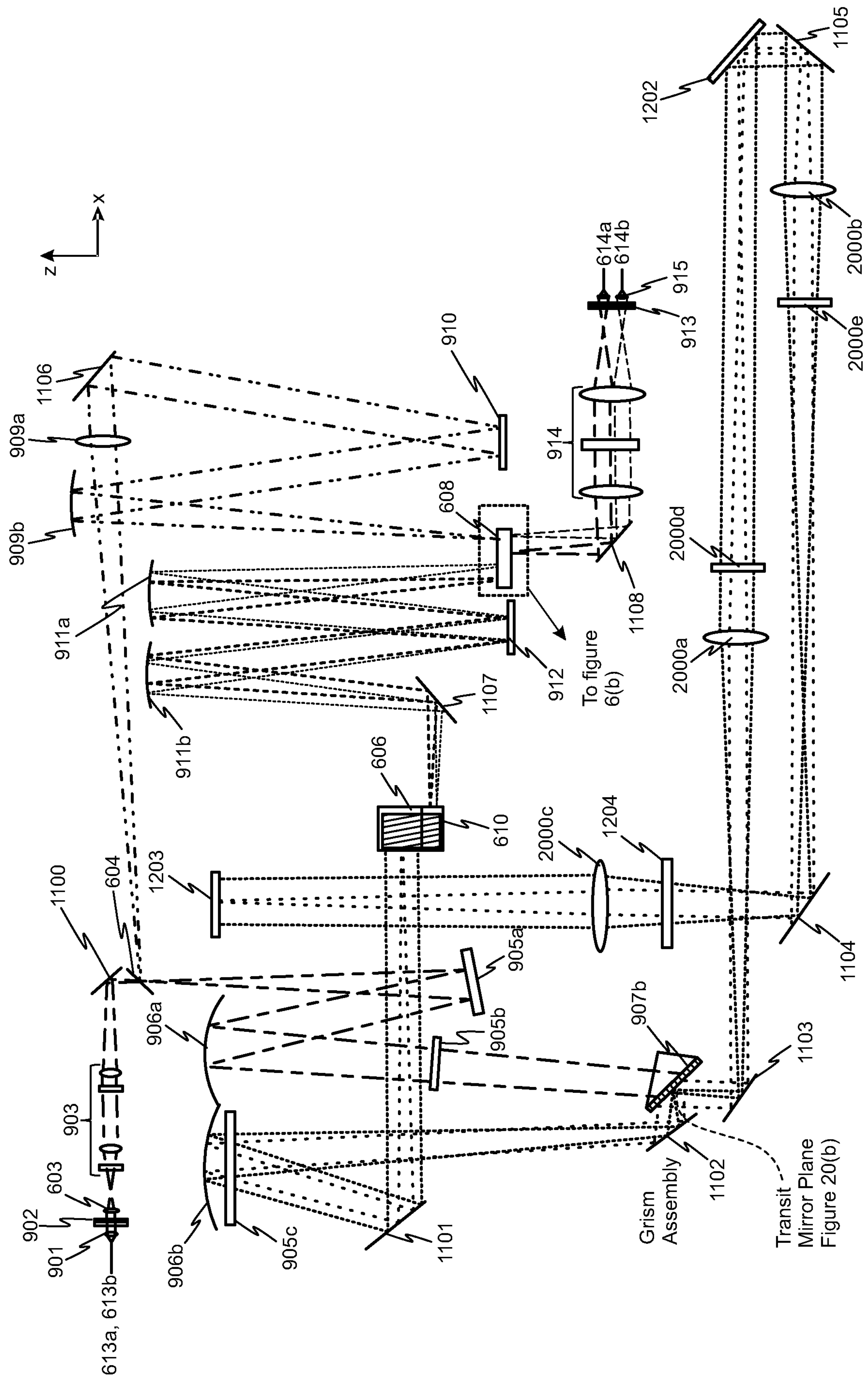
x
z
1106
909a
909b
910
608
1108
914
913
915
614a
614b
1202
1105
2000b
2000e
2000d
2000a
911a
911b
912
To figure 6(b)
1107
606
610
1100
604
1203
2000c
1204
1104
905a
906a
905b
907b
1103
903
603
902
901
613a, 613b
906b
905c
1101
Grism Assembly
1102
Transit Mirror Plane Figure 20(b)

FIG. 20(a)

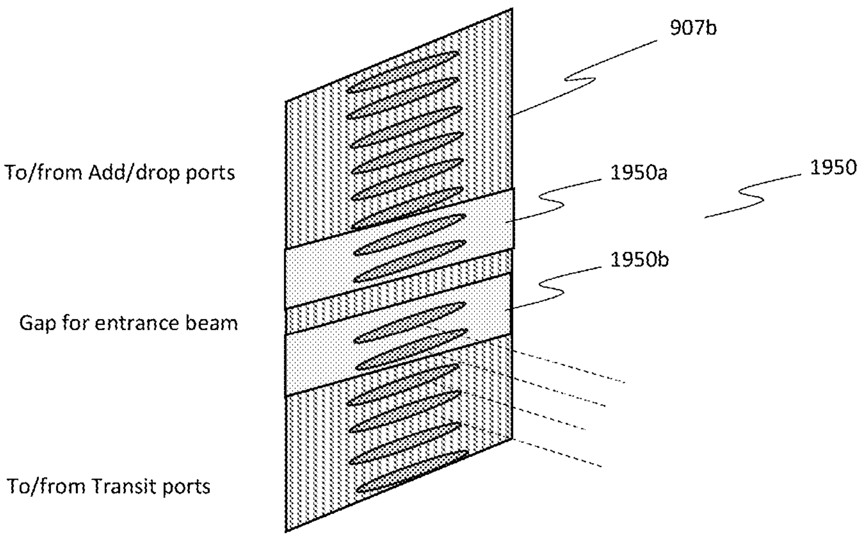
907b
To/from Add/drop ports
1950a
1950
1950b
Gap for entrance beam
To/from Transit ports

FIG. 20(b)

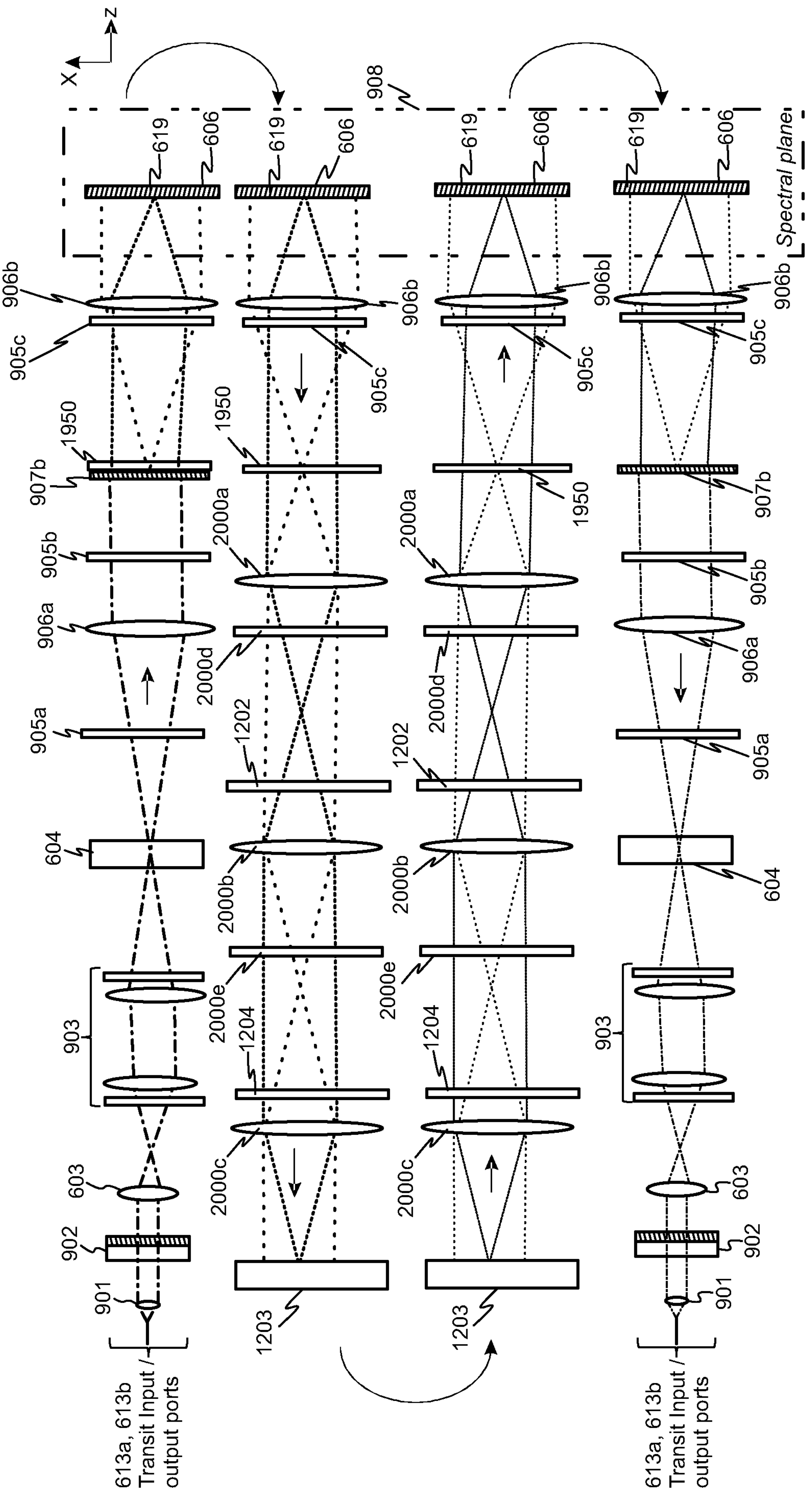
z
x
908
619
606
Spectral plane
906b
905c
1950
907b
905b
906a
905a
604
903
603
902
901
613a, 613b
Transit Input / output ports
2000a
2000d
1202
2000b
2000e
1204
2000c
1203

FIG. 20(c)

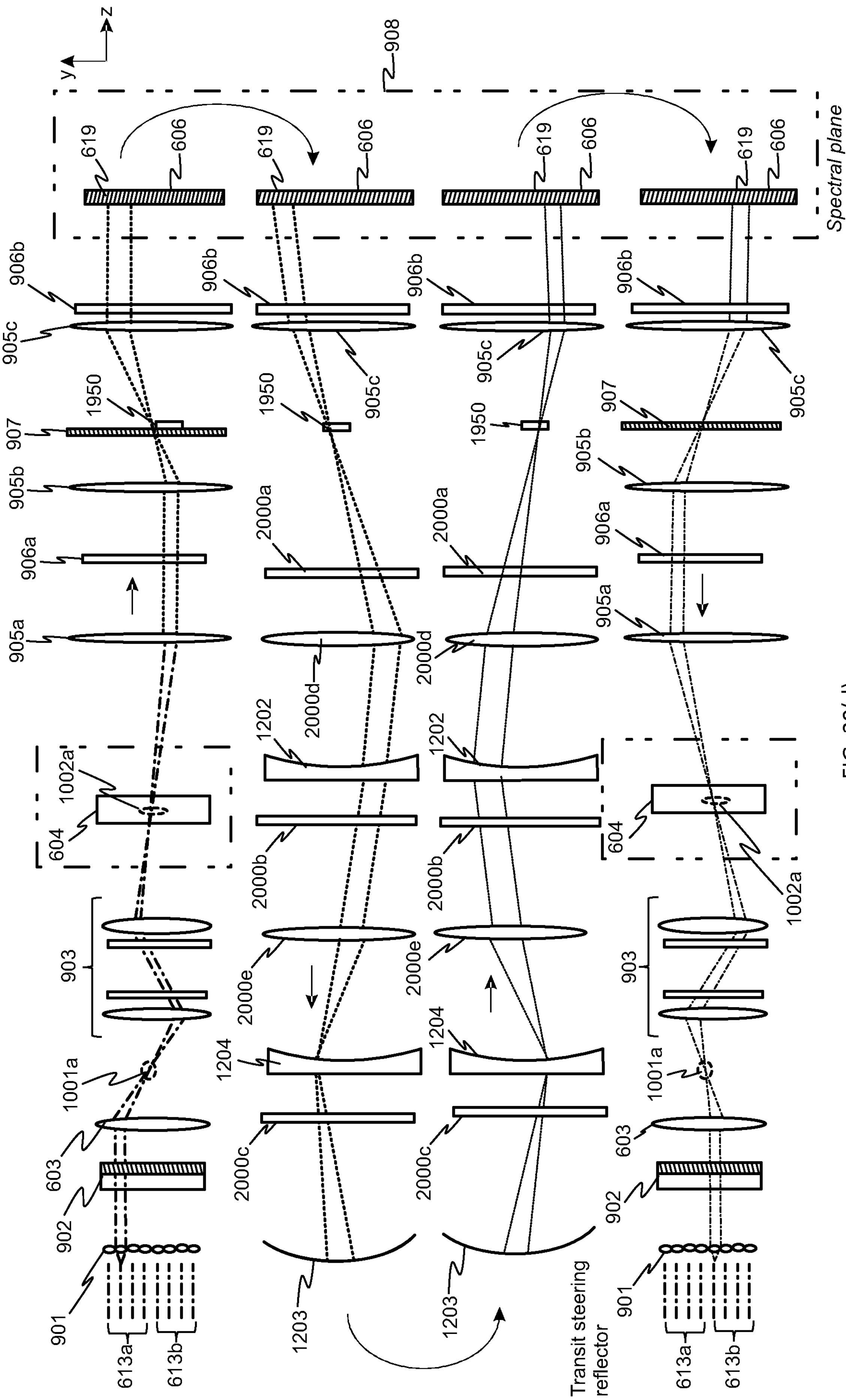
z
y
908
Spectral plane
619
606
906b
905c
1950
907
905b
906a
905a
2000a
2000d
1202
1002a
604
2000b
903
2000e
1001a
1204
603
902
2000c
901
613a
613b
1203
Transit steering reflector

FIG. 20(d)

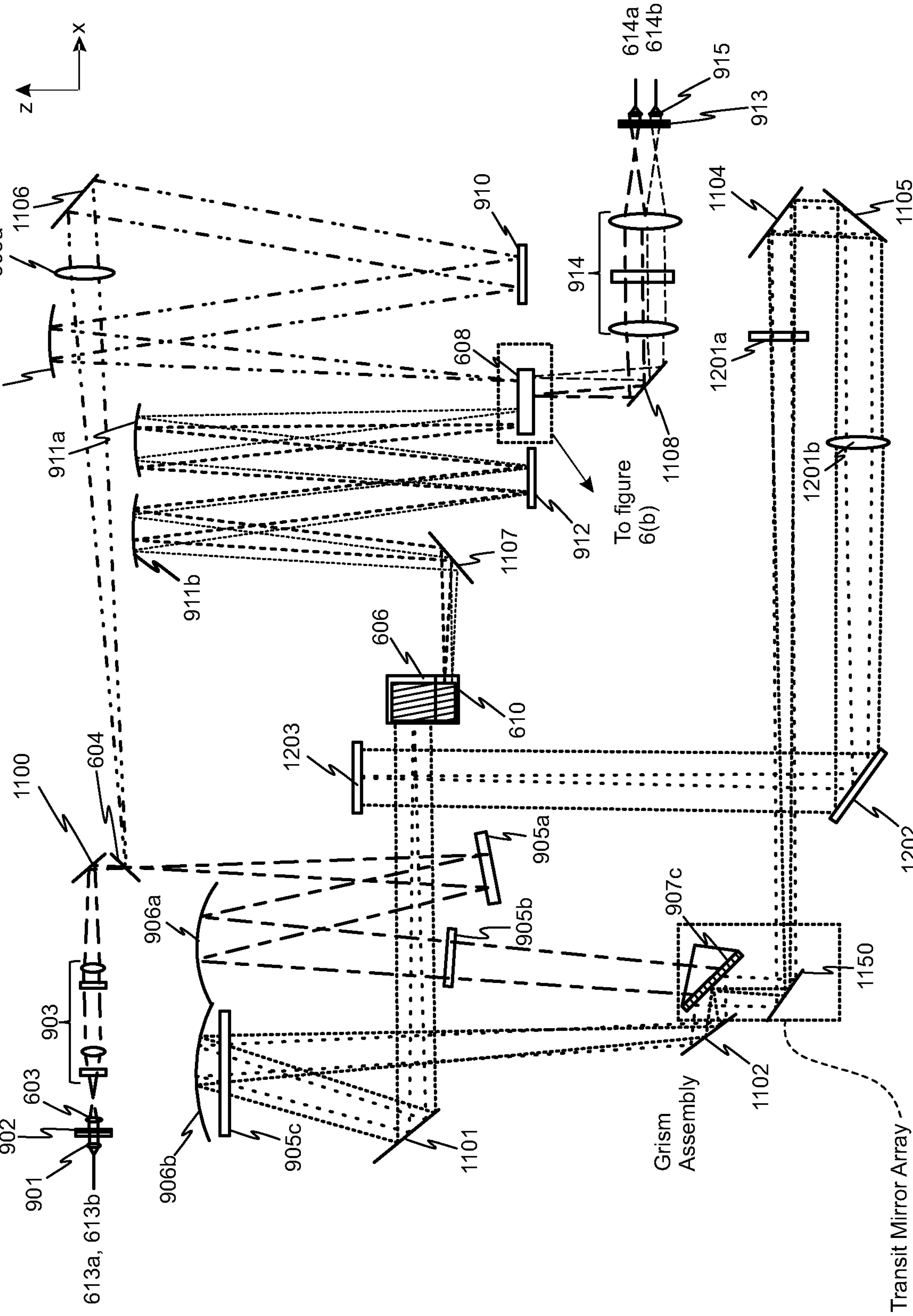
x
z
1106
909a
909b
910
608
911a
911b
912
To figure 6(b)
1107
1108
914
913
915
614a
614b
1104
1105
1201a
1201b
606
610
1203
1202
1100
604
905a
905b
906a
903
907c
1150
603
902
901
613a, 613b
906b
905c
1101
1102
Grism Assembly
Transit Mirror Array Figure 21(b)

FIG. 21(a)

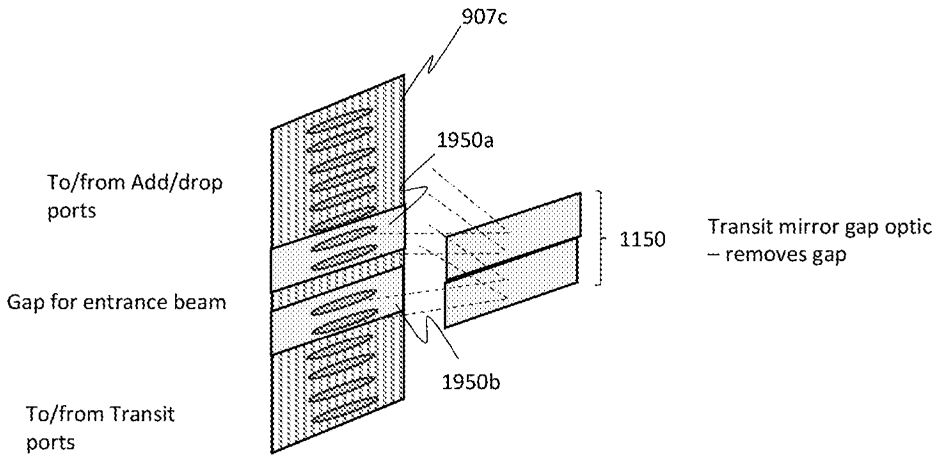
907c
1950a
To/from Add/drop ports
1150
Transit mirror gap optic – removes gap
Gap for entrance beam
1950b
To/from Transit ports

FIG. 21(b)

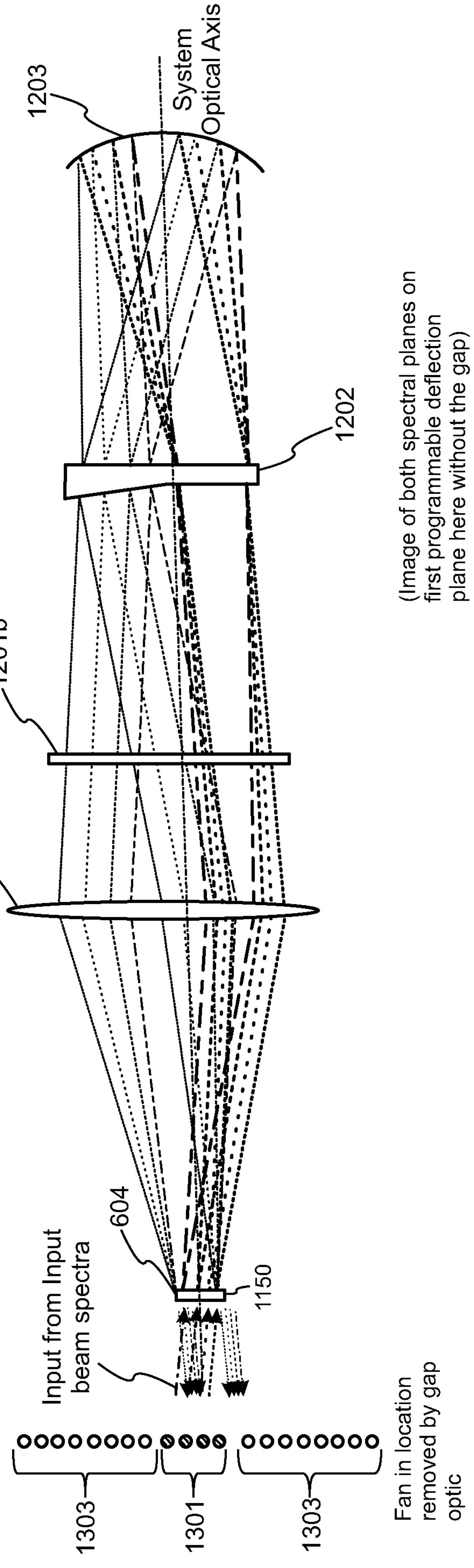
1203
System
Optical Axis
1202
(Image of both spectral planes on
first programmable deflection
plane here without the gap)
1201b
1201a
604
Input from Input
beam spectra
1150
1303
1301
1303
Fan in location
removed by gap
optic

FIG. 21(c)

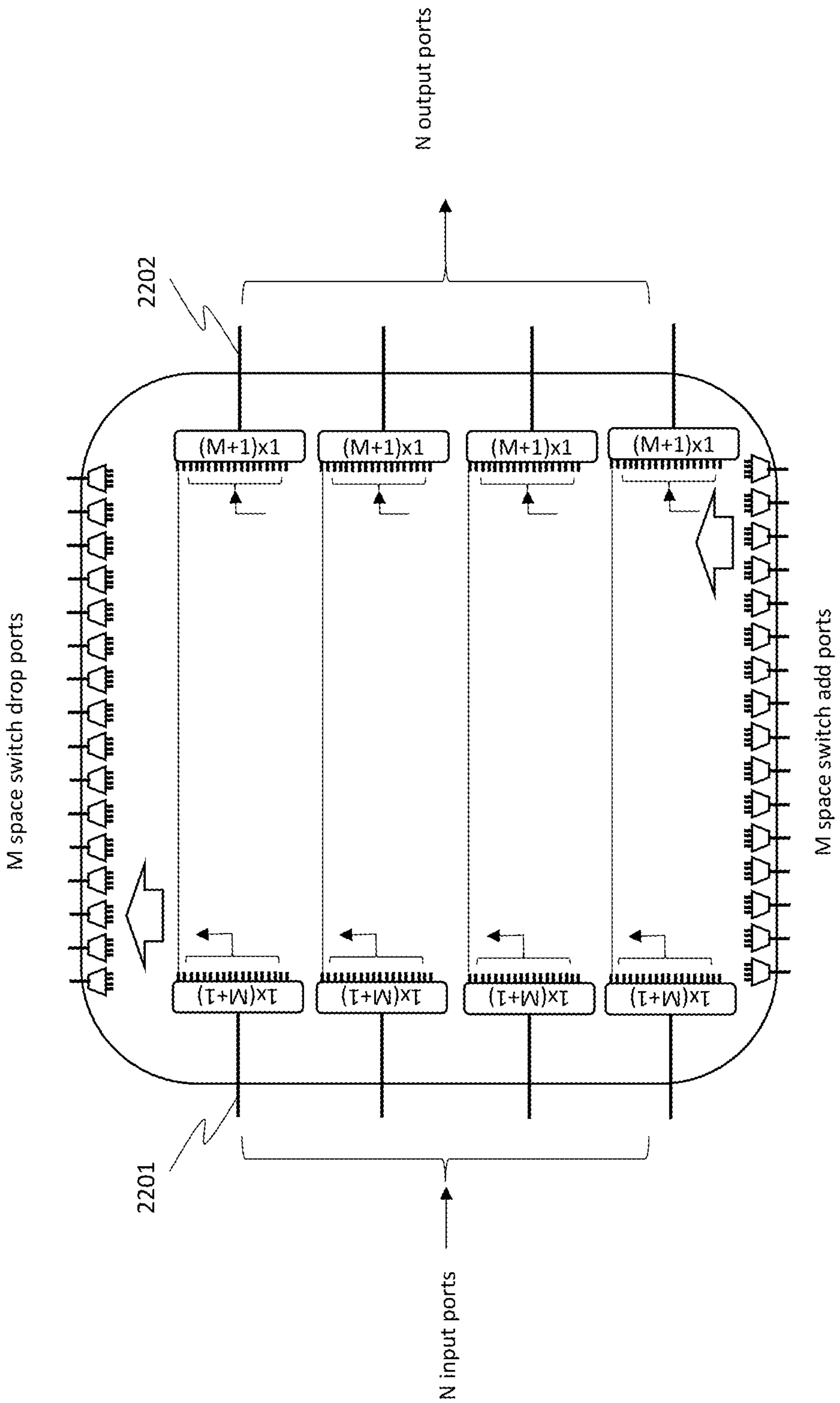
N output ports
2202
(M+1)x1
M space switch drop ports
M space switch add ports
1x(M+1)
2201
N input ports

FIG. 22

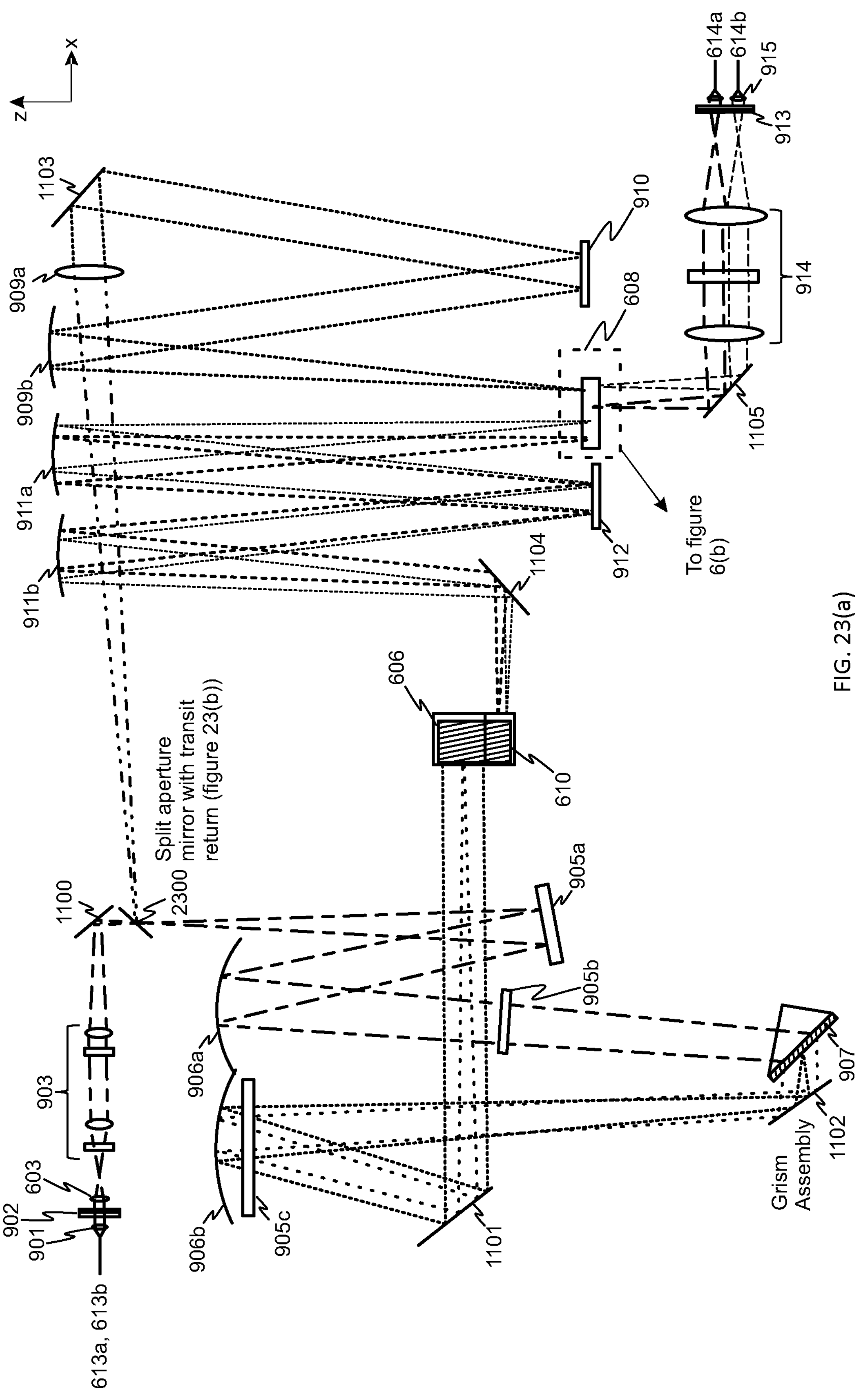
z
x
1103
909a
909b
911a
911b
910
608
912
To figure
6(b)
1104
1105
914
913
915
614a
614b
606
610
Split aperture
mirror with transit
return (figure 23(b))
1100
2300
905a
905b
905c
906a
906b
903
603
902
901
613a, 613b
1101
907
1102
Grism
Assembly

FIG. 23(a)

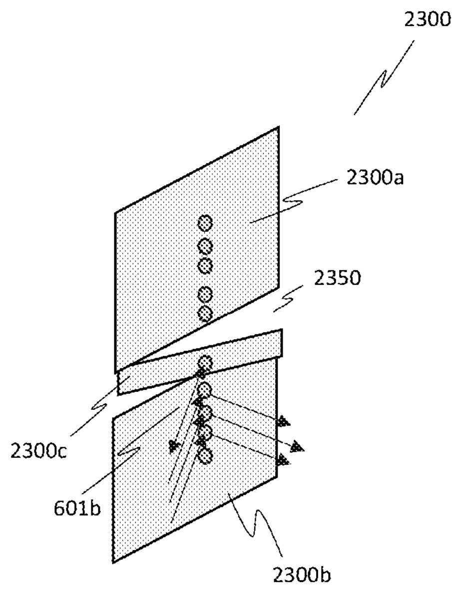

FIG. 23(b)

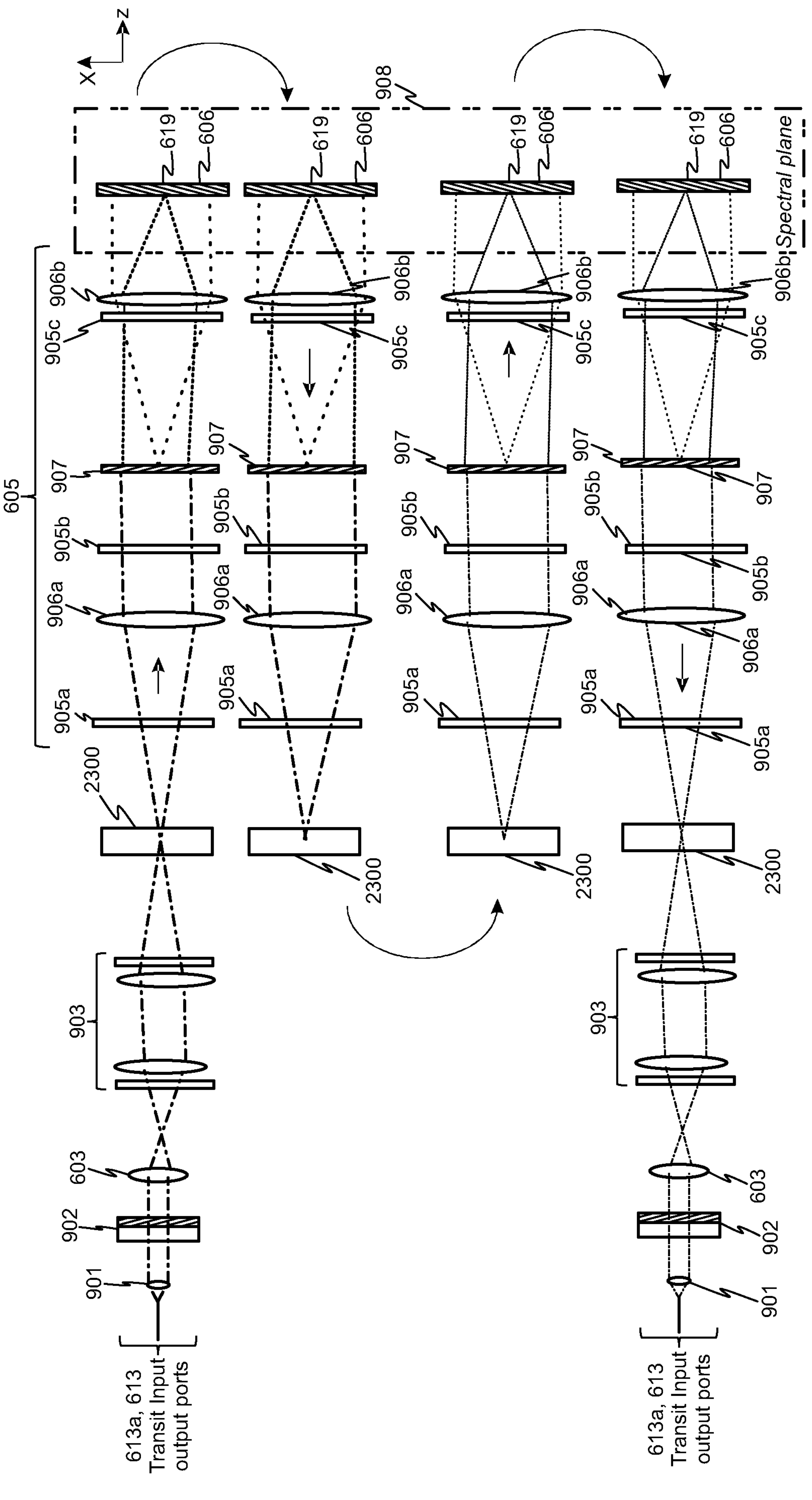
z
x
908
619
606
Spectral plane
605
906b
905c
907
905b
906a
905a
2300
903
603
902
901
613a, 613
Transit Input
output ports

FIG. 23(c)

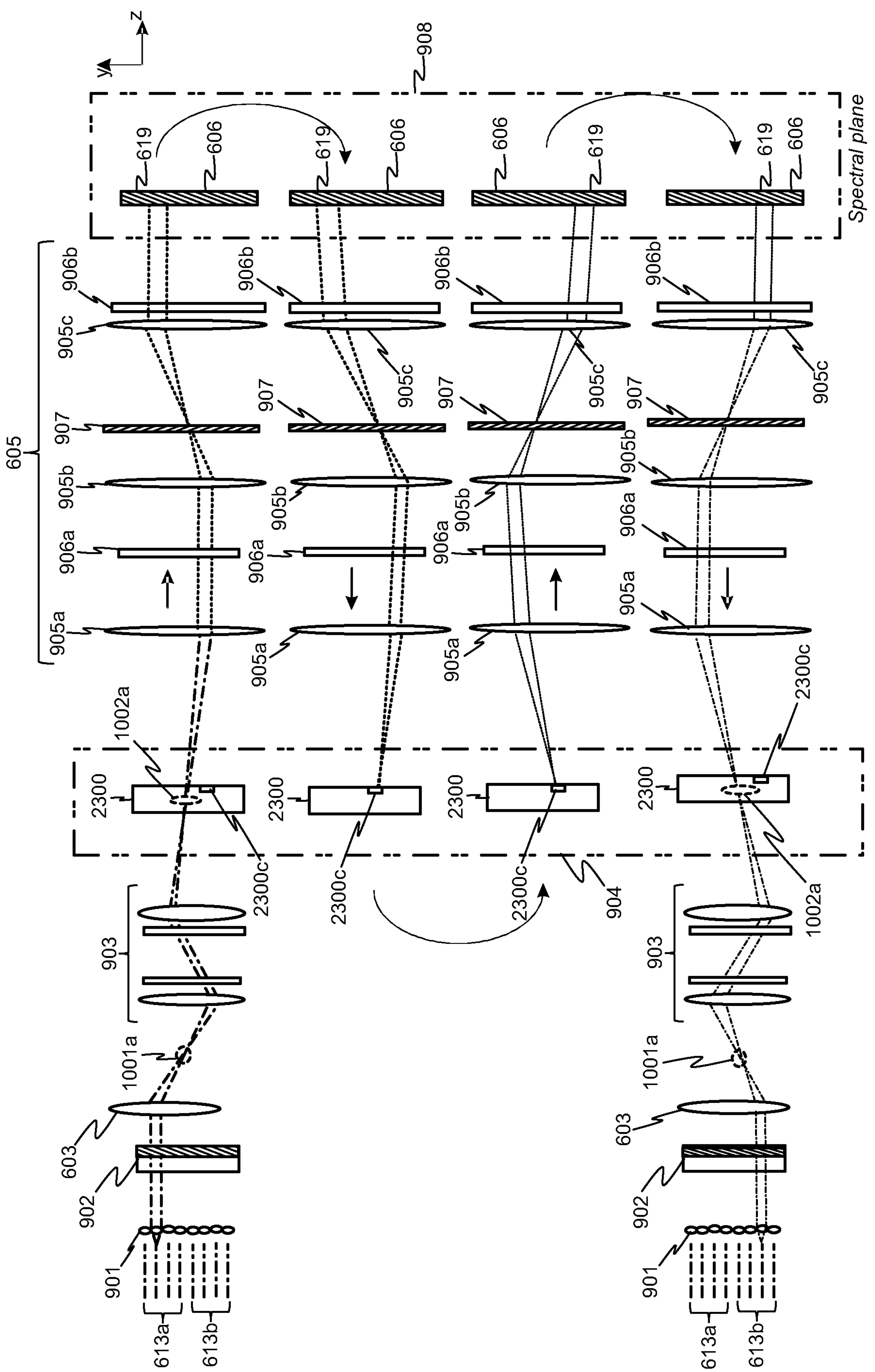
z
y
908
Spectral plane
619
606
906b
905c
907
905b
906a
905a
605
1002a
2300
2300c
2300c
904
903
1001a
603
902
901
613a
613b

FIG. 23(d)

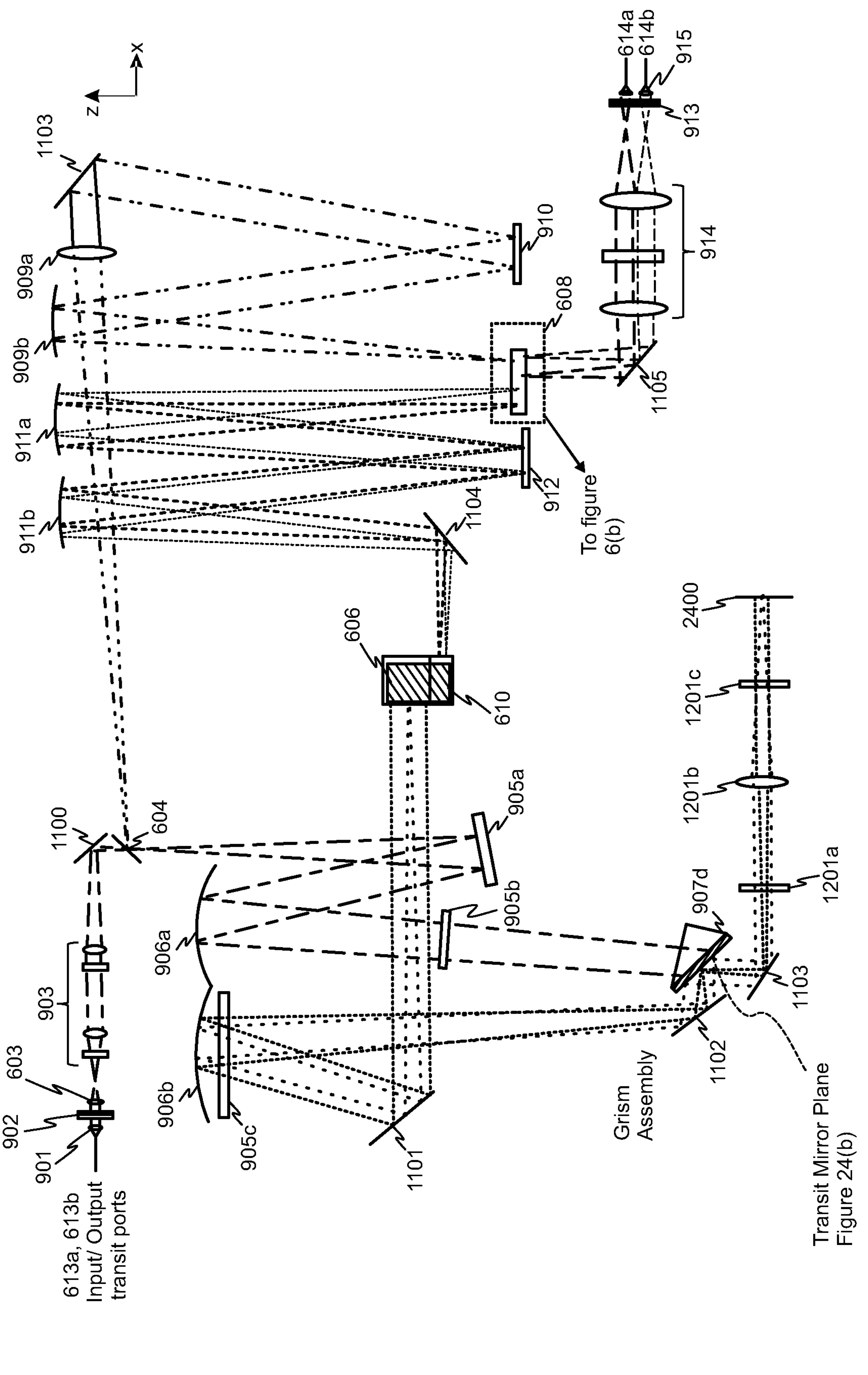
x
z
1103
909a
909b
911a
911b
910
608
1105
912
To figure 6(b)
1104
614a
614b
915
913
914
606
610
905a
905b
1100
604
903
603
902
901
613a, 613b Input/ Output transit ports
906a
906b
905c
1101
907d
1103
1102
Grism Assembly
Transit Mirror Plane Figure 24(b)
1201a
1201b
1201c
2400

FIG. 24(a)

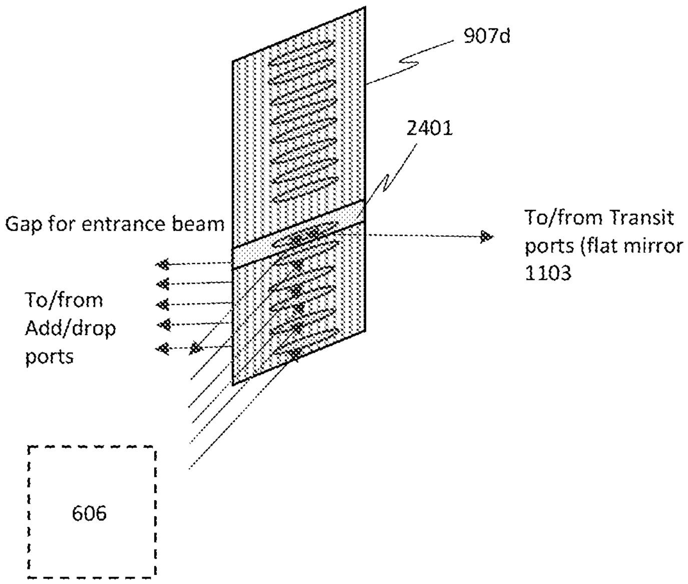
907d
2401
Gap for entrance beam
To/from Transit ports (flat mirror 1103
To/from Add/drop ports
606

FIG. 24(b)

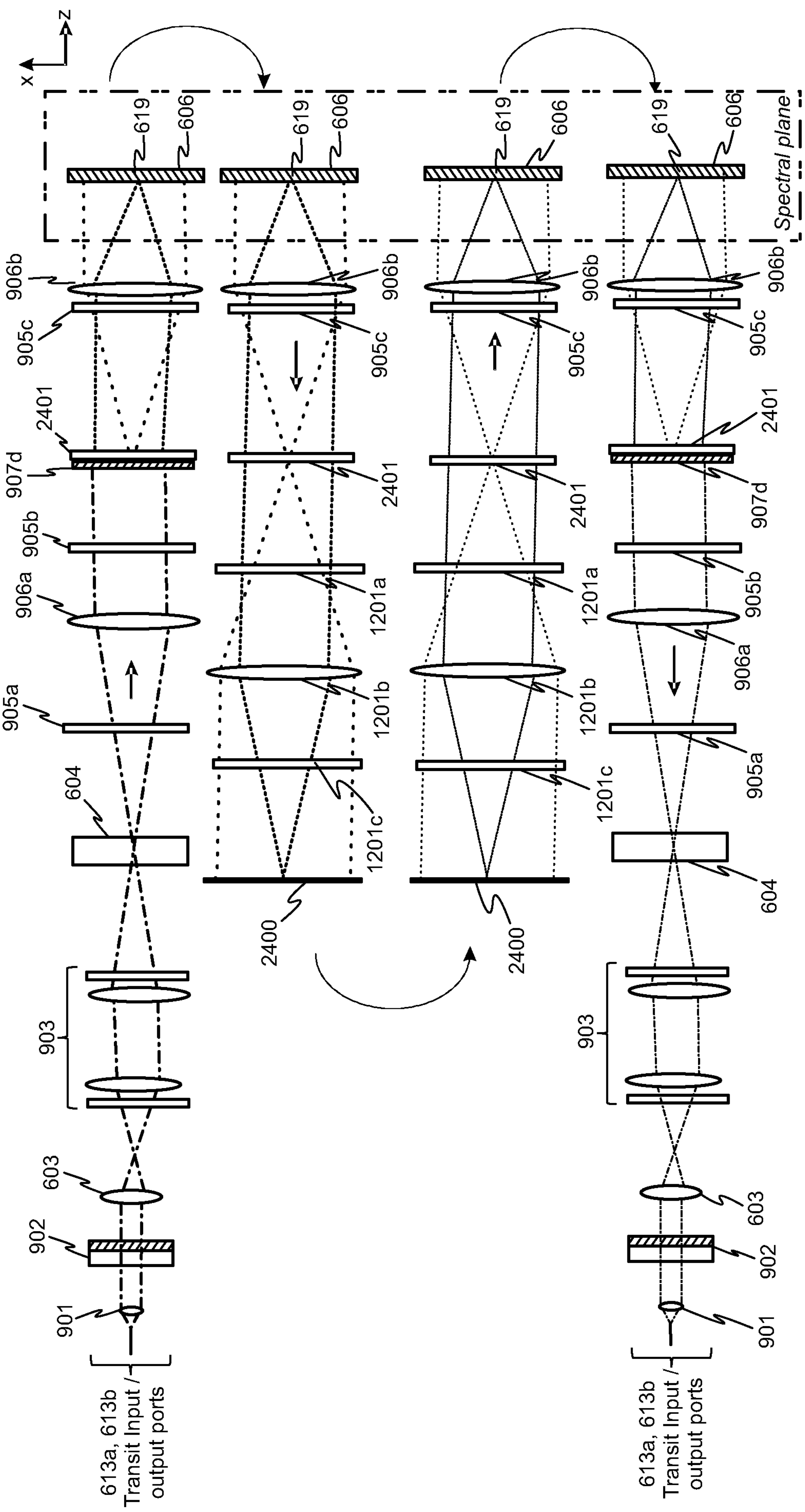
z
x
619
606
Spectral plane
906b
905c
2401
907d
905b
906a
905a
604
903
603
902
901
613a, 613b
Transit Input / output ports
1201a
1201b
1201c
2400

FIG. 24(c)

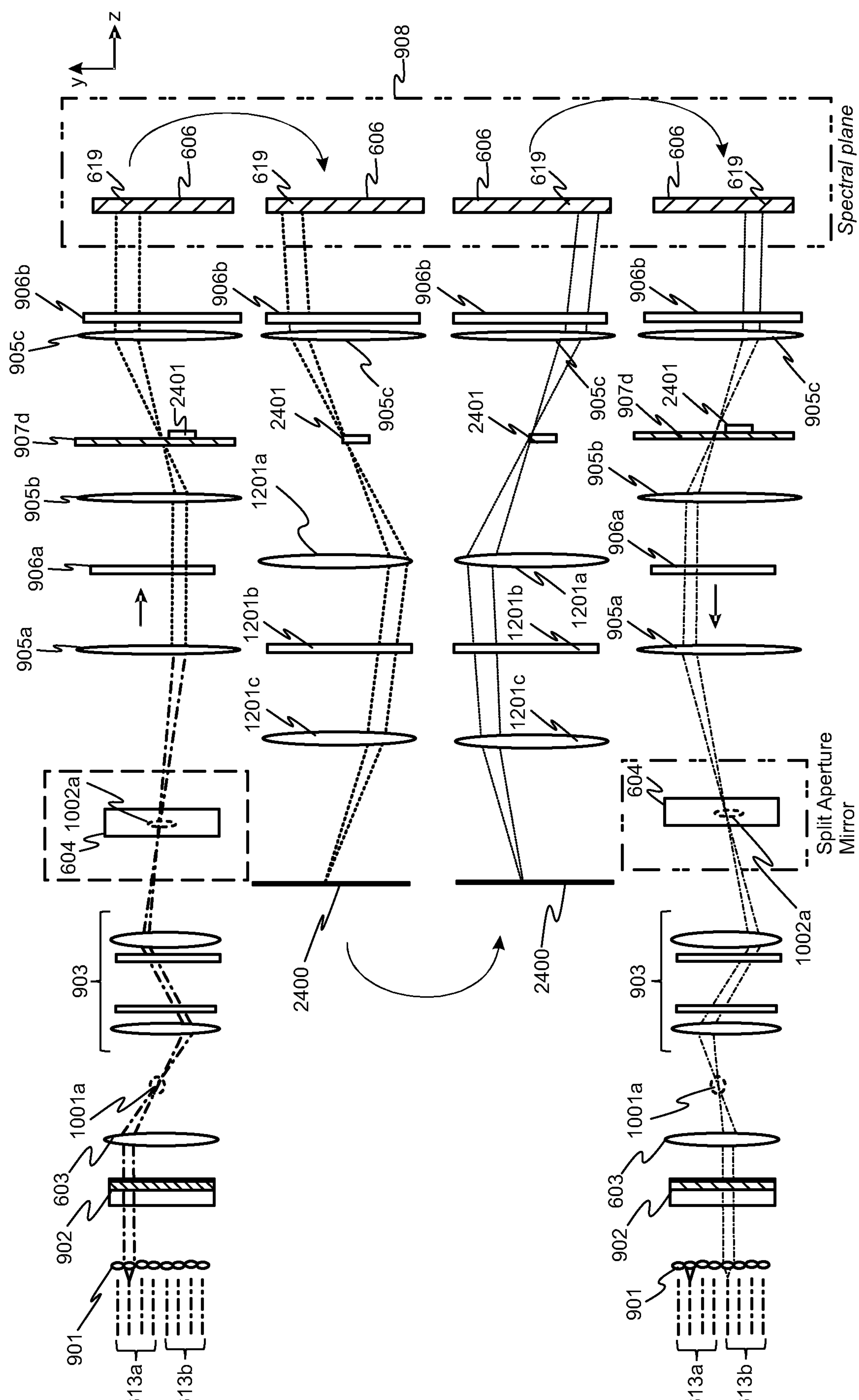
z
y
908
Spectral plane
619
606
906b
905c
2401
907d
905b
906a
905a
1201a
1201b
1201c
604
1002a
Split Aperture Mirror
2400
903
1001a
603
902
901
613a
613b

FIG. 24(d)

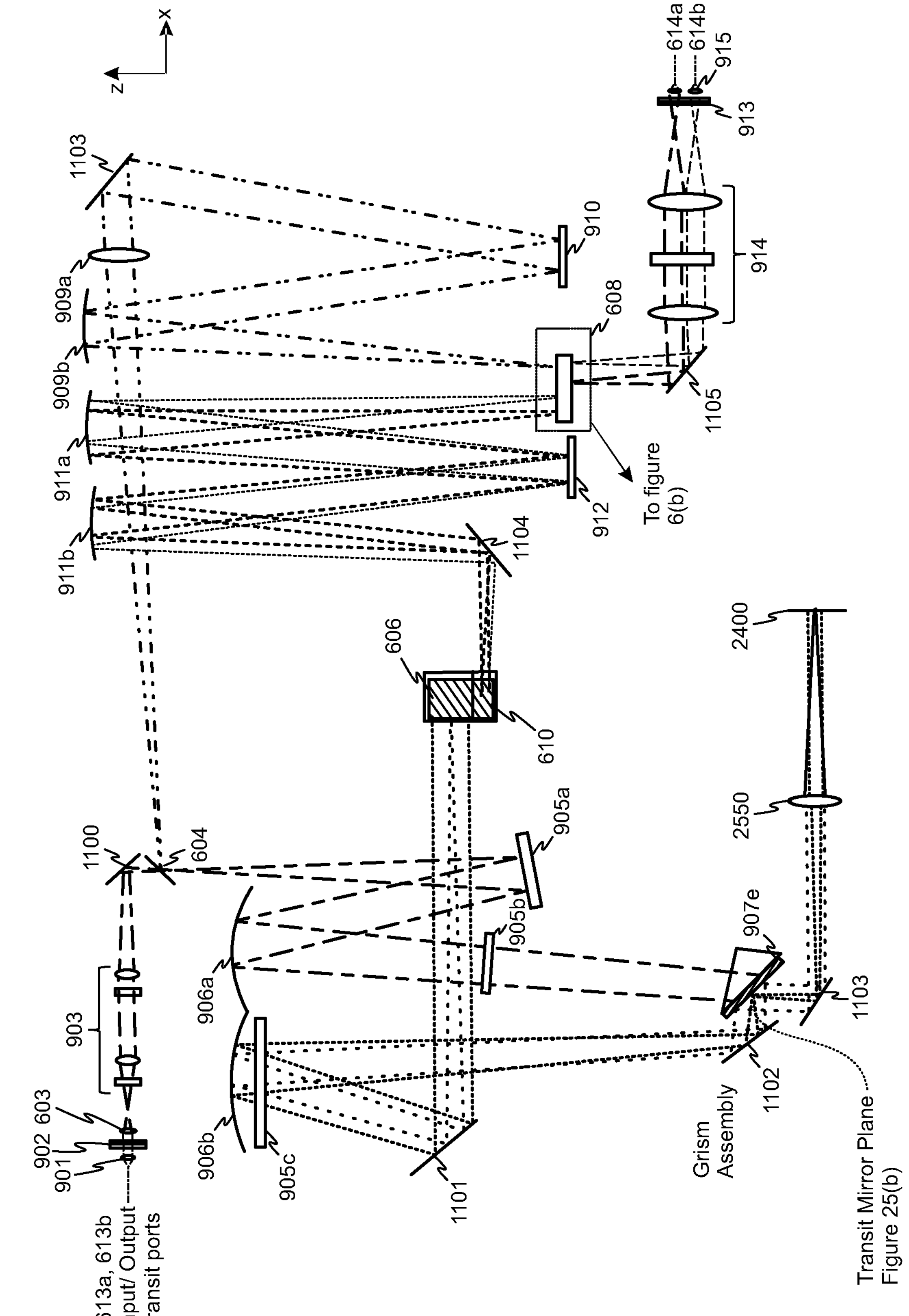
x
z
1103
909a
909b
911a
911b
910
608
912
To figure 6(b)
1104
1105
913
914
915
614a
614b
606
610
2400
2550
1100
604
905a
905b
907e
1103
906a
906b
905c
903
902
603
901
613a, 613b Input/ Output transit ports
1101
1102
Grism Assembly
Transit Mirror Plane Figure 25(b)

FIG. 25(a)

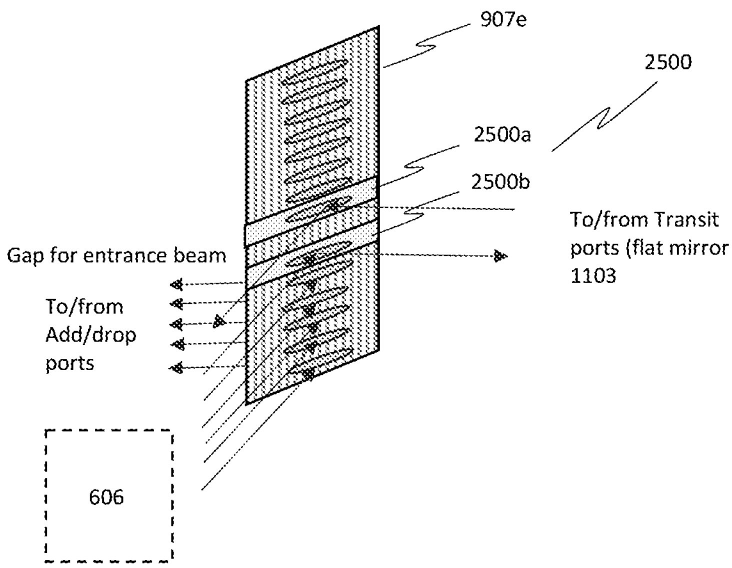
907e
2500
2500a
2500b
To/from Transit ports (flat mirror 1103
Gap for entrance beam
To/from Add/drop ports
606

FIG. 25(b)

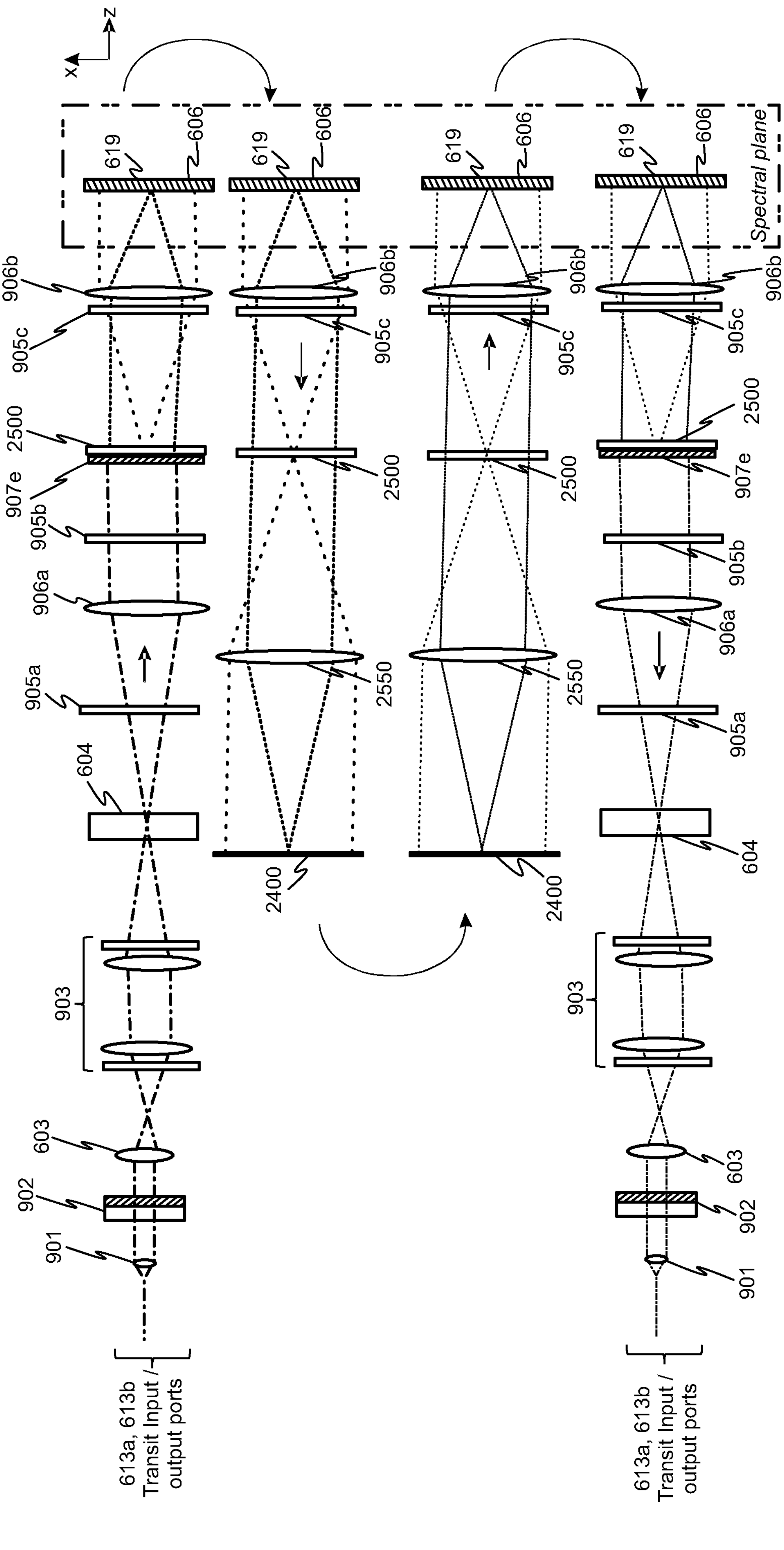
z
x
619
606
Spectral plane
906b
905c
2500
907e
905b
906a
905a
604
2550
2400
903
603
902
901
613a, 613b
Transit Input /
output ports

FIG. 25(c)

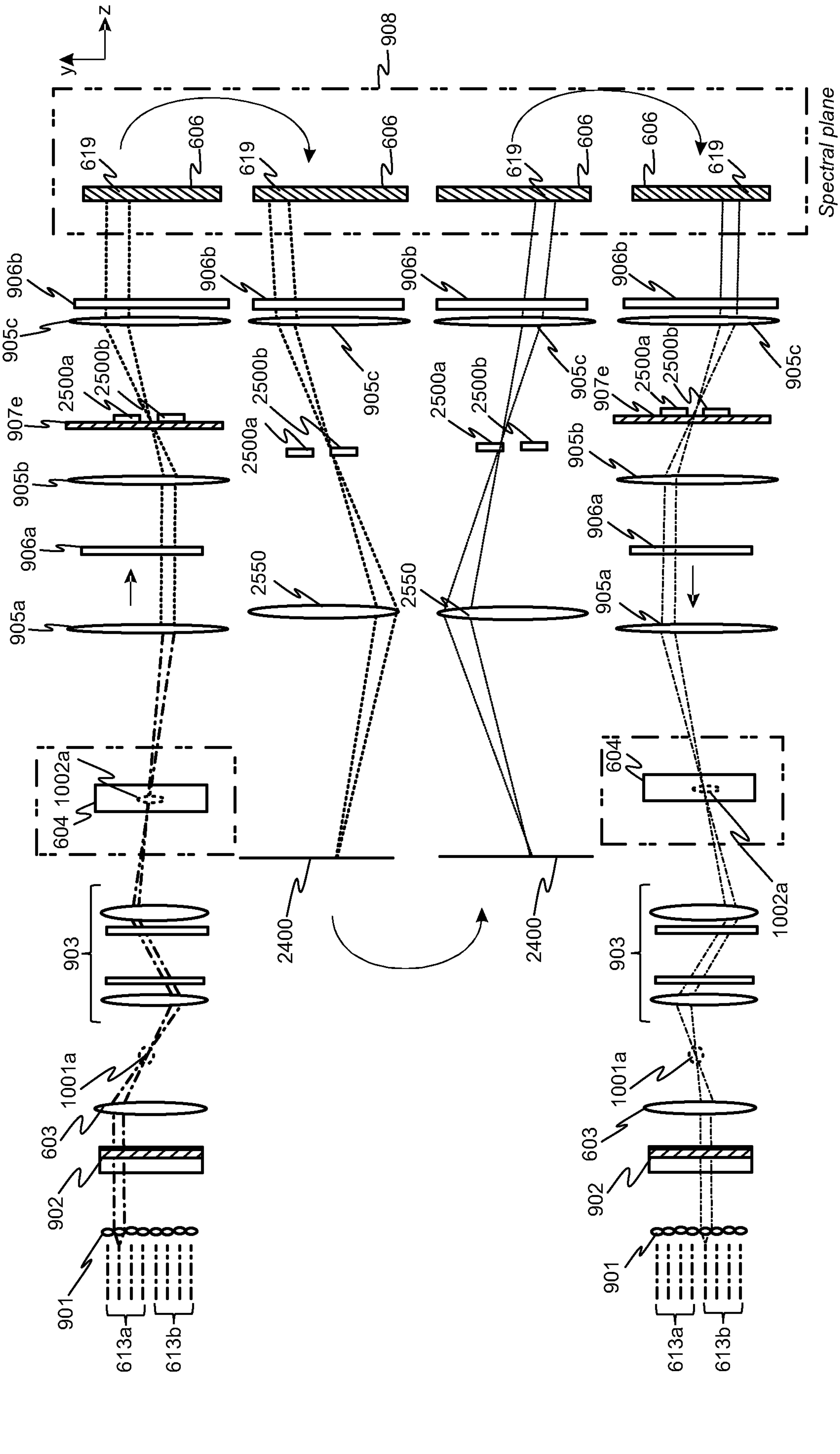
z
y
908
Spectral plane
619
606
906b
905c
2500a
2500b
907e
905b
906a
905a
2550
604
1002a
2400
903
1001a
603
902
901
613a
613b

FIG. 25(d)

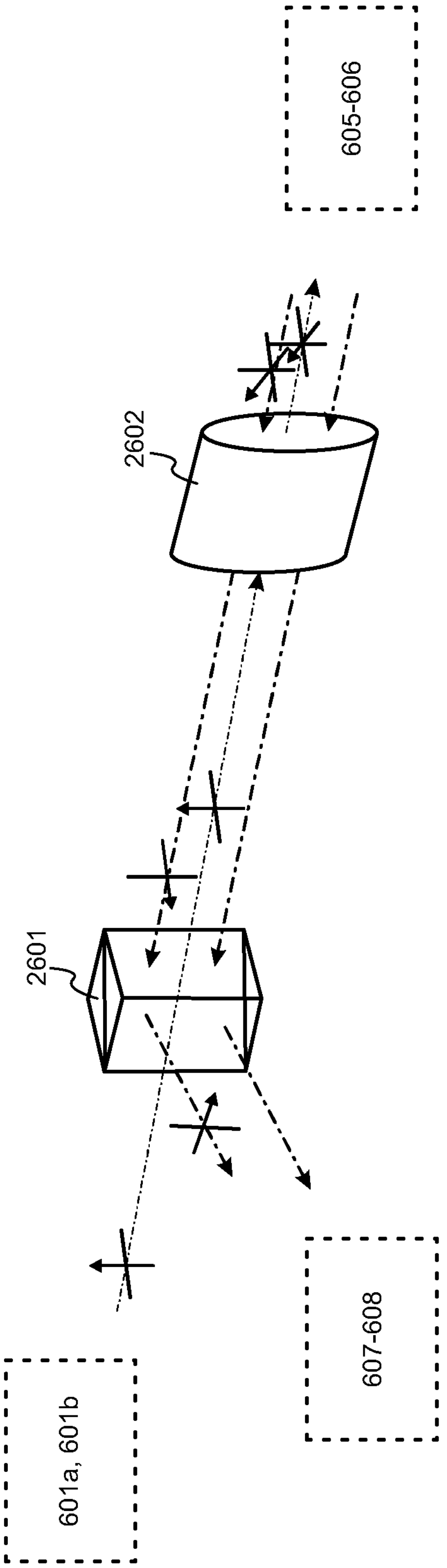

FIG. 26

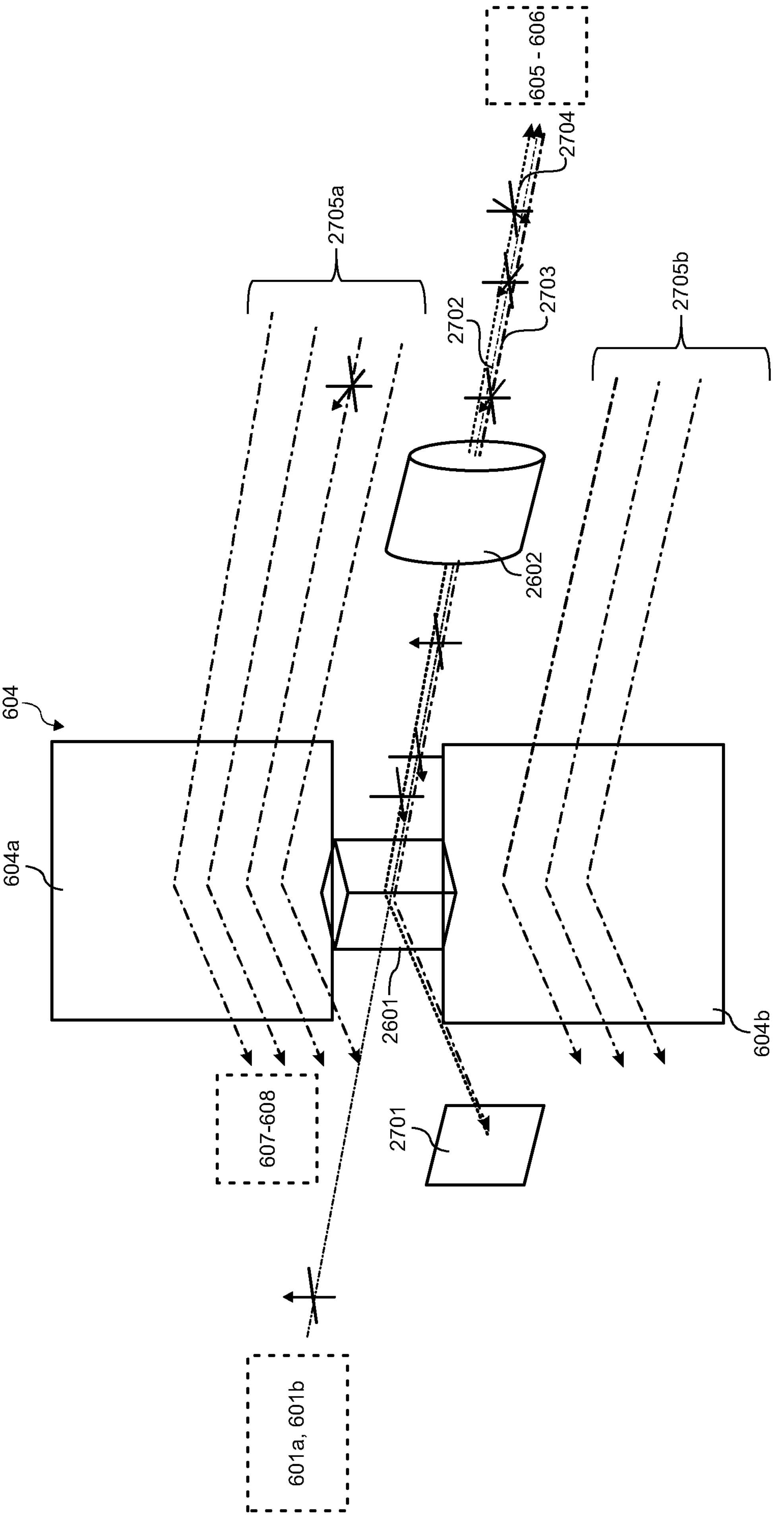
605 - 606
2704
2705a
2703
2702
2705b
2602
604
604a
2601
604b
607-608
2701
601a, 601b

FIG. 27

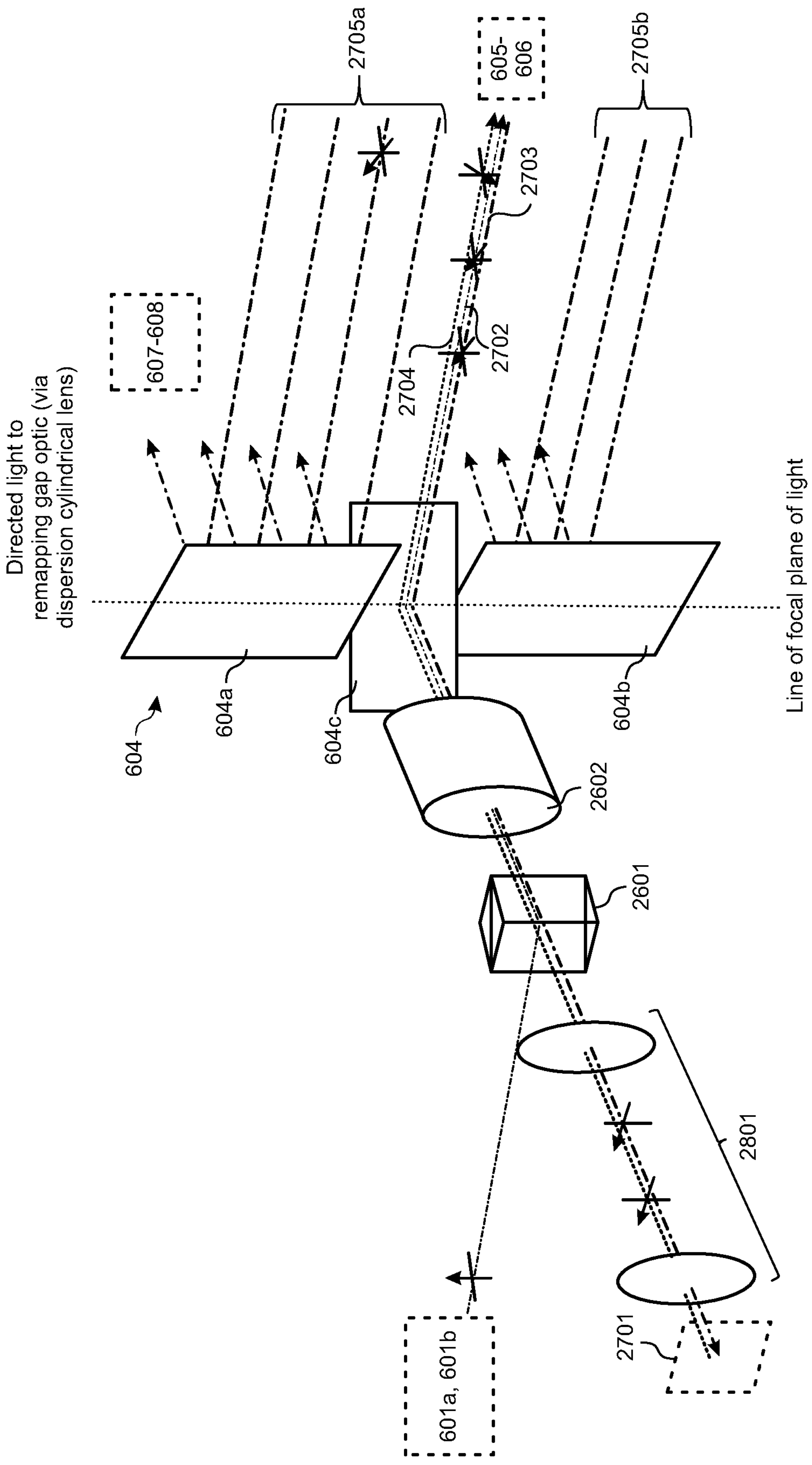
2705a
605-
606
2705b
607-608
2703
2702
2704
Directed light to
remapping gap optic (via
dispersion cylindrical lens)
Line of focal plane of light
604
604a
604c
604b
2602
2601
2801
601a, 601b
2701

FIG. 28

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2023/053248

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04Q11/00
ADD.

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)
H04Q

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

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

EPO-Internal, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	US 2020/073054 A1 (YANG HAINING [GB] ET AL) 5 March 2020 (2020-03-05) paragraph [0070] - paragraph [0073]; figure 2a -----	1-17, 25-27 18-24
Y	YAMAGUCHI KEITA ET AL: "Route-and-Select Type Wavelength Cross Connect for Core-Shuffling of 7-Core MCFs with Spatial and Planar Optical Circuit", ECOC 2016, 22 September 2016 (2016-09-22), pages 752-754, XP093141727, the whole document ----- -/--	1-17, 25-27

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

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 March 2024	27/03/2024

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

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INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2023/053248

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	YANG HAINING ET AL: "24 [1x12] Wavelength Selective Switches Integrated on a Single 4k LCoS Device", JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE, USA, vol. 39, no. 4, 15 June 2020 (2020-06-15), pages 1033-1039, XP011836277, ISSN: 0733-8724, DOI: 10.1109/JLT.2020.3002716 [retrieved on 2021-02-04] the whole document -----	1-27
A	YANG HAINING ET AL: "Low-cost CDC ROADM architecture based on stacked wavelength selective switches", JOURNAL OF OPTICAL COMMUNICATIONS AND NETWORKING, IEEE, USA, vol. 9, no. 5, 1 May 2017 (2017-05-01), pages 375-384, XP011649201, ISSN: 1943-0620, DOI: 10.1364/JOCN.9.000375 [retrieved on 2017-05-11] the whole document -----	1-27
A	US 8 300 995 B2 (COLBOURNE PAUL [CA]; JDS UNIPHASE CORP [US]) 30 October 2012 (2012-10-30) figures 4a-4c,5a,5b -----	1-27

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2023/053248

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		US 2020073054 A1	05-03-2020
		WO 2018104725 A1	14-06-2018
US 8300995 B2	30-10-2012	NONE	