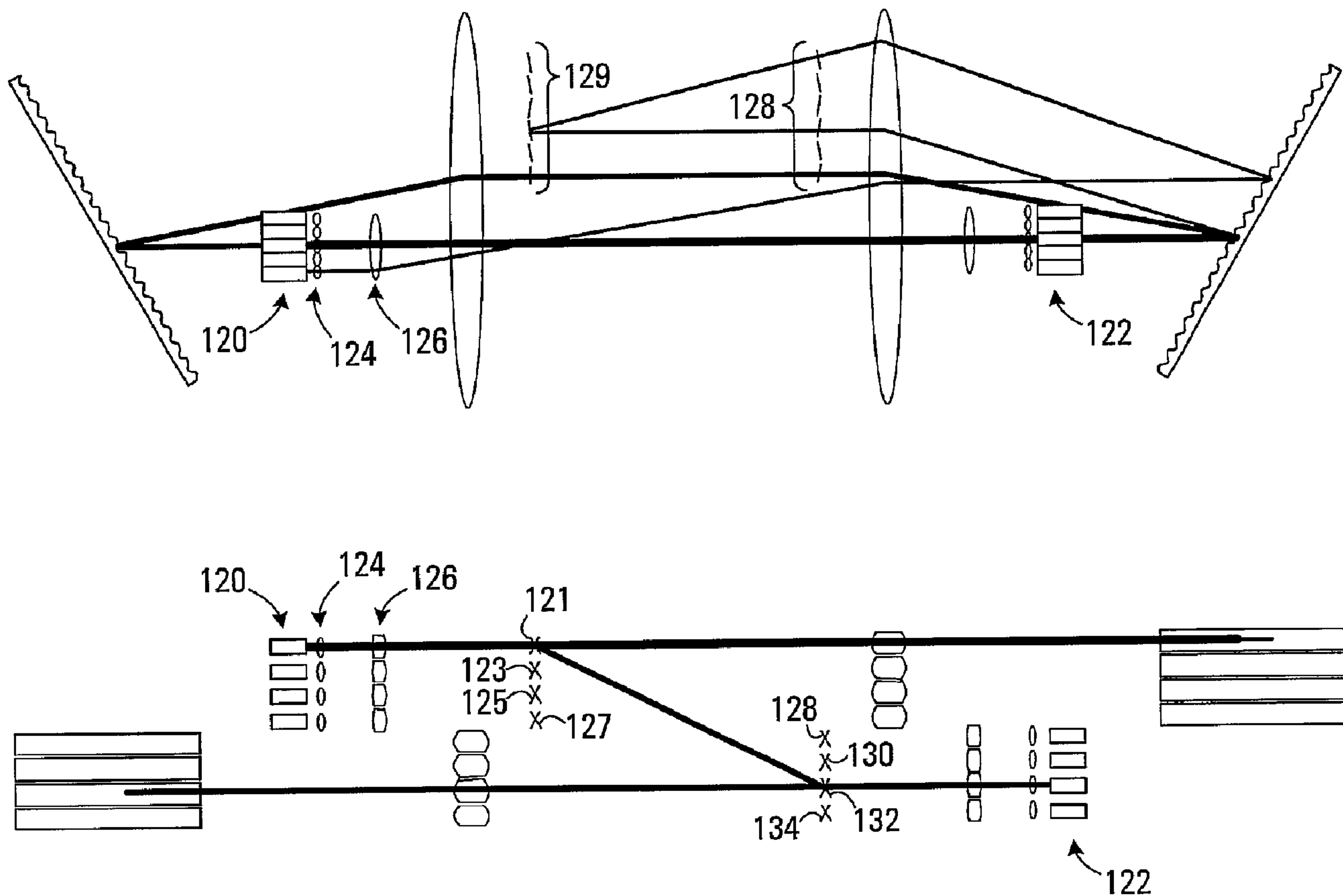




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(57) Abrégé/Abstract:

A wavelength cross connect is provided in which wavelength channels are individually switchable from one of a first set of ports to one of a second set of ports. Add and drop capability is provided on the sets of ports. Some embodiments feature a single row of



(57) **Abrégé(suite)/Abstract(continued):**

ports, while others feature two dimensional arrays of ports. Some embodiments employ one dispersive element per port, and others employ one dispersive element per row of ports. Embodiments featuring transmissive and non-transmissive switching elements are provided.

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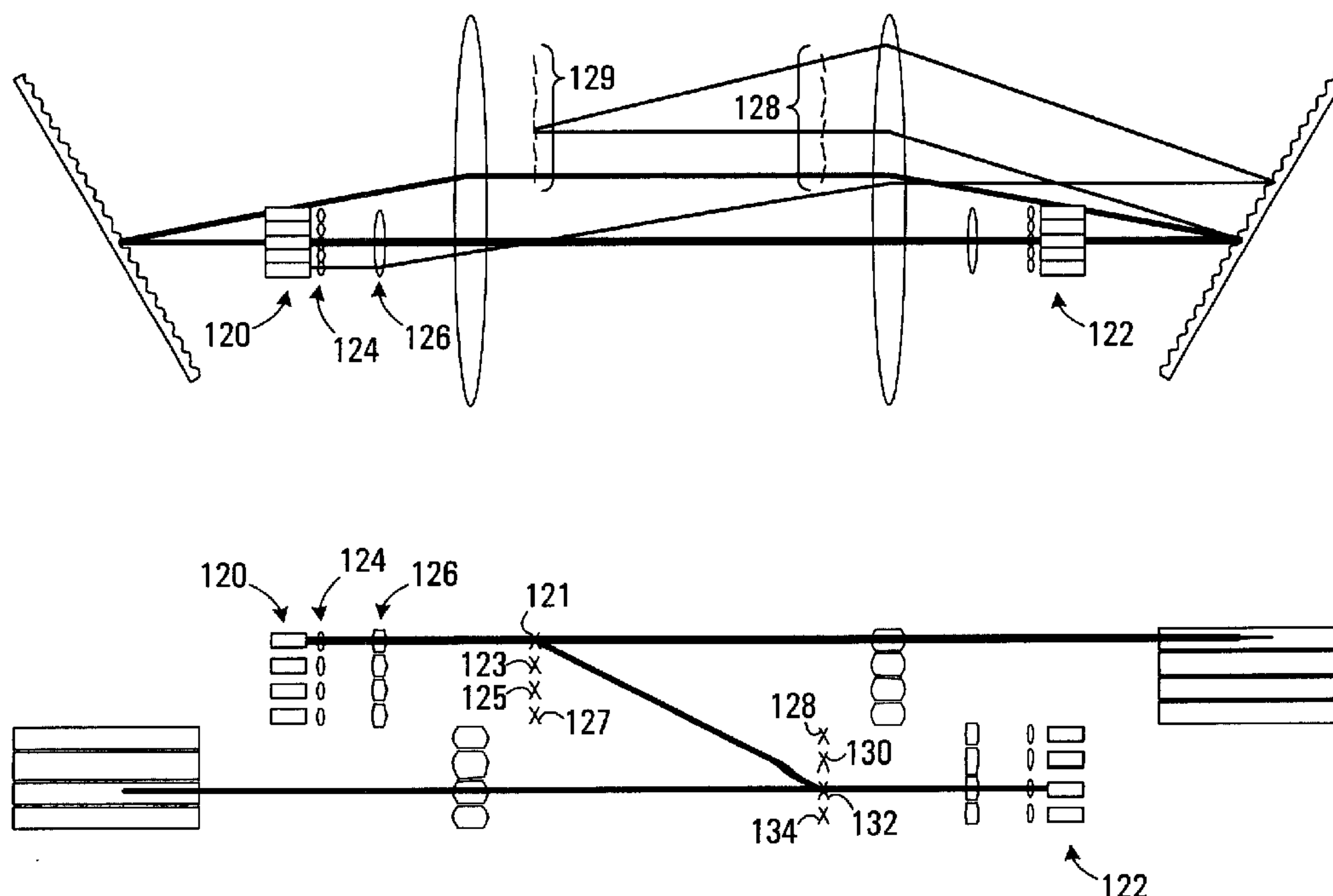
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(54) Title: WAVELENGTH CROSS-CONNECT



(57) Abstract: A wavelength cross connect is provided in which wavelength channels are individually switchable from one of a first set of ports to one of a second set of ports. Add and drop capability is provided on the sets of ports. Some embodiments feature a single row of ports, while others feature two dimensional arrays of ports. Some embodiments employ one dispersive element per port, and others employ one dispersive element per row of ports. Embodiments featuring transmissive and non-transmissive switching elements are provided.

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WAVELENGTH CROSS-CONNECT

FIELD OF THE INVENTION

This invention relates to the field of DWDM fibre optics telecommunications and in particular to the field of
5 all-optical switching.

BACKGROUND OF THE INVENTION

The advent of DWDM fibre optics telecommunications systems in the early 1990s have enabled a dramatic increase in the transmission capacity over point-to-point links. This was
10 achieved through multiplexing of a large number of individually modulated light beams of different wavelengths onto the same optical fibre. Typical systems installed today would have 64 or more independent channels precisely aligned onto an ITU-T standardized grid at 100 GHz, 50 GHz or even narrower channel
15 spacing. With routine modulation speeds of 10 Gb/s and attaining 40 Gb/s in laboratory experiments, it is not unusual to obtain aggregated capacities in the order of several terabits per second of information being transmitted onto a single optical fibre (S. Bigo, Optical Fibre Communications
20 conference, WX 3, pp. 362-364, Anaheim, 2002). At the same time, electrical switching capacities have been growing at a much slower rate, with current largest electrical switch matrices limited to typically 640 Gb/s in a single stage. Furthermore, the cost of converting the signal from optical to
25 electrical for switching and then back from electrical to optical becomes prohibitively expensive as the number of

optical channel increases. All optical switching technologies are therefore becoming more and more attractive to manage the enormous bandwidth being transmitted over optical fibres.

A typical all-optical switch would consist of a large
5 core all-optical switch matrix surrounded by DWDM demultiplexers and multiplexers at each fibre interface. However, for large number of wavelengths channels per optical fibre, this leads to a very large switching core size: for example, a 50 GHz channel spacing system with 128 channels per
10 fibre would require a 1024x1024 switching matrix to switch traffic between 8 incoming fibres to 8 outgoing fibres on a per wavelength basis. Large optical switching matrices are hard to fabricate, complex to control, require overwhelming fibre management and are very expensive. Furthermore, in the absence
15 of wavelength conversion, only a sub-set of the switching matrix capacity is actually in use: each wavelength being switched independently, only 128 8x8 independent connections are used in the 1024x1024 available (0.8% of the overall switching capacity). This huge inefficiency is the primary
20 reason for considering a wavelength switching architecture in which the DWDM demultiplexing and multiplexing are integrated with the switching function.

An example of a wavelength selective all-optical switch is called a wavelength selective cross-connect WSXC (R.
25 E. Wagner, Journal of Lightwave Technology, Vol. 14, No. 6, June 1996, also US patent 6,097,859) by Solgaard et al. Such a device generally has N incoming fibres and N outgoing fibres, each fibre being capable of transporting M wavelength channels.

The WXC enables independent switching of each of the M wavelength channels from the N incoming fibres to the N outgoing fibres. It is functionally equivalent to an input array of N wavelength demultiplexers routed to an output array of N wavelength multiplexers through an array of M NxN optical switches. In such a WXC, there are MxNxN possible optical paths, which is exactly the required flexibility in the absence of wavelength conversion. For example, in the case mentioned above of a 128 channel system at 50 GHz spacing with 8 fibres in and 8 fibres out, the standard large optical core based switch would have over a million possible connections, whereas only 8192 are needed, which is exactly what the WXC architecture enables (128x8x8).

SUMMARY OF THE INVENTION

According to one broad aspect, the invention provides a wavelength cross connect comprising: a first plurality of lenses stacked vertically; a second plurality of lenses stacked vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first plurality of lenses; a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses; a second plurality of dispersive elements, with one dispersive element substantially in a second focal plane of each of said second plurality of lenses; a first array of switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses; a second array of switching elements controllable in two directions, the

second array being substantially in a first focal plane of each of said second plurality of lenses; in a first plurality of optical ports a respective optical port positioned to input light onto/receive light from each of said first plurality of lenses; in a second plurality of optical ports a respective optical port positioned to input light onto/receive light from each of said second plurality of lenses; wherein light entering any of said first plurality of optical ports or said second plurality of ports is switchable to any of the first plurality of optical ports and any of said second plurality of optical ports.

In some embodiments, the switching elements are MEMS switching elements.

In some embodiments, each first bulk optical element is selected from a group consisting of a lens or a curved mirror.

In some embodiments, the dispersive element is selected from a group consisting of: a diffraction grating, either reflection and transmission type, prisms.

According to another broad aspect, the invention provides a wavelength cross connect comprising: a first plurality of lenses stacked vertically; a second plurality of lenses stacked vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first plurality of lenses; a first dispersive element at least part of which is substantially in a first focal plane of each of said first plurality of lenses; a second dispersive element at

least part of which is substantially in a second focal plane of each of said second plurality of lenses; a first array of switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses; a second array of switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses; in a first plurality of optical ports a respective optical port positioned to input light onto/receive light from each of said first plurality of lenses; in a second plurality of optical ports a respective optical port positioned to input light onto/receive light from each of said second plurality of lenses; wherein light entering any of said first plurality of optical ports or said second plurality of ports is switchable to any of the first plurality of optical ports and any of said second plurality of optical ports.

In some embodiments, the switching elements are MEMS switching elements.

In some embodiments, each first bulk optical element is selected from a group consisting of a lens or a curved mirror.

In some embodiments, the dispersive element is selected from a group consisting of: a diffraction grating, either reflection and transmission type, prisms.

According to another broad aspect, the invention provides a wavelength cross connect comprising: a first plurality of lenses stacked vertically; a second plurality of

lenses stacked vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first plurality of lenses; a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses; a second plurality of dispersive elements, with one dispersive element substantially in a second focal plane of each of said second plurality of lenses; a first array of transmissive switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses; a second array of transmissive switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses; in a first plurality of optical ports a respective optical port positioned to input light onto/receive light from each of said first plurality of lenses; in a second plurality of optical ports a respective optical port positioned to input light onto/receive light from each of said second plurality of lenses; wherein light entering any of said first plurality of optical ports or said second plurality of ports is switchable to any of the first plurality of optical ports and any of said second plurality of optical ports.

In some embodiments, the transmissive switching elements are one of a liquid crystal beam steering element, an acousto-optic beam deflector, part of a solid state phase array, a controllable hologram, and a periodically poled Lithium Niobate beam deflector.

In some embodiments, each first bulk optical element is selected from a group consisting of a lens or a curved mirror.

In some embodiments, the dispersive element is
5 selected from a group consisting of: a diffraction grating, either reflection and transmission type, prisms.

According to another broad aspect, the invention provides a wavelength cross connect comprising: a first plurality of lenses stacked vertically; a second plurality of
10 lenses stacked vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first plurality of lenses; a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses; a second
15 plurality of dispersive elements, with one dispersive element substantially in a second focal plane of each of said second plurality of lenses; a first array of switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first
20 plurality of lenses; a second array of switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses; a first two dimensional array of optical ports; a second two dimensional array of optical ports; for
25 each row of said first two dimensional array of optical ports, a respective first bulk optical element having optical power and having a fourth focal plane substantially coplanar with said first focal plane of said second plurality of lenses; for

each row of said second two dimensional array of optical ports,
a respective second bulk optical element having optical power
and having a fifth focal plane substantially coplanar with said
second focal plane of said first plurality of lenses; wherein
5 each wavelength channel of a WDM signal entering at a port of
said first array of optical ports is individually switchable to
any of the port in first array of optical ports in a same row
as the port where the WDM signal entered and any of the second
array of optical ports through appropriate control of the array
10 of switching elements.

In some embodiments, the switching elements are MEMS
switching elements.

In some embodiments, each bulk optical element is a
lens or a curved mirror.

15 In some embodiments, the dispersive element is
selected from a group comprising: a diffraction grating,
either reflection and transmission type, prisms.

According to another broad aspect, the invention
provides a wavelength cross connect comprising: a first
20 plurality of lenses stacked vertically; a second plurality of
lenses stacked vertically, spaced from said first plurality of
lenses, non-overlapping in vertical space with said first
plurality of lenses; a first plurality of dispersive elements,
with one dispersive element substantially in a first focal
25 plane of each of said first plurality of lenses; a second
plurality of dispersive elements, with one dispersive element
substantially in a second focal plane of each of said second

plurality of lenses; a first array of switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses; a second array of switching elements
5 controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses; a first two dimensional array of optical ports; a second two dimensional array of optical ports; a first bulk optical element having optical power and having a fourth
10 focal plane substantially coplanar with said first focal plane of said second plurality of lenses; a second optical element having optical power and having a fifth focal plane substantially coplanar with said second focal plane of said first plurality of lenses; wherein each wavelength channel of a
15 WDM signal entering at port of said first array of optical ports is individually switchable to any of the port in first array of optical ports in a same row as the port where the WDM signal entered and any of the second array of optical ports through appropriate control of the array of switching elements.

20 In some embodiments, the switching elements are MEMS switching elements.

In some embodiments, each bulk optical element is a lens or a curved mirror.

25 In some embodiments, the dispersive element is selected from a group comprising: a diffraction grating, either reflection and transmission type, prisms.

According to another broad aspect, the invention provides an arrangement comprising: a first two dimensional array of optical ports; a first two dimensional array of waveguide dispersive elements on a plurality of waveguide substrates, with one waveguide dispersive element per optical port in said first two dimensional array of optical ports, the first two dimensional array of waveguide dispersive elements collectively having a first output plane; for each row of said first two dimensional array of optical ports, a respective first bulk optical element having optical power and having a first focal plane substantially coplanar with said first output plane, and having a second focal plane; a first array of switching elements substantially in the second focal plane, each switching element being adapted to switch in both a horizontal and vertical direction; a second two dimensional array of optical ports; a second two dimensional array of waveguide dispersive elements on a plurality of waveguide substrates, with one waveguide dispersive element per optical port in said second two dimensional array of optical ports, the second two dimensional array of waveguide dispersive elements collectively having a second output plane; for each row of said second two dimensional array of optical ports, a respective second bulk optical element having optical power and having a fifth focal plane and having a sixth focal plane substantially coplanar with the second output plane; a second array of switching elements substantially in the fifth focal plane, each switching element being adapted to switch in both a horizontal and vertical direction; wherein each wavelength channel of a WDM signal entering at one of said first array of optical ports is individually switchable to any of the optical ports of the

first array in a same row as the port through which the signal entered and any of the optical ports of the second array through appropriate control of the array of switching elements.

In some embodiments, the switching elements are MEMS
5 switching elements.

In some embodiments, each bulk optical element having optical power is a lens or a curved mirror.

In some embodiments, the dispersive elements comprise arrayed waveguide gratings or Echelle gratings.

10 According to another broad aspect, the invention provides an arrangement comprising: a first two dimensional array of optical ports; a first two dimensional array of waveguide dispersive elements on a plurality of waveguide substrates, with one waveguide dispersive element per optical
15 port in said first two dimensional array of optical ports, the first two dimensional array of waveguide dispersive elements collectively having a first output plane; a first bulk optical element having optical power and having a first focal plane substantially coplanar with said first output plane, and having
20 a second focal plane; a first array of switching elements substantially in the second focal plane, each switching element being adapted to switch in both a horizontal and vertical direction; a second two dimensional array of optical ports; a second two dimensional array of waveguide dispersive elements
25 on a plurality of waveguide substrates, with one waveguide dispersive element per optical port in said second two dimensional array of optical ports, the second two dimensional

array of waveguide dispersive elements collectively having a second output plane; a second bulk optical element having optical power and having a fifth focal plane and having a sixth focal plane substantially coplanar with the second output
5 plane; a second array of switching elements substantially in the fifth focal plane, each switching element being adapted to switch in both a horizontal and vertical direction; wherein each wavelength channel of a WDM signal entering at one of said first array of optical ports is individually switchable to any
10 of the optical ports of the first array in a same row as the port through which the signal entered and any of the optical ports of the second array through appropriate control of the array of switching elements.

In some embodiments, the switching elements are MEMS
15 switching elements.

In some embodiments, each bulk optical element having optical power is a lens or a curved mirror.

In some embodiments, the dispersive elements comprise arrayed waveguide gratings or Echelle gratings.

20 According to another broad aspect, the invention provides a wavelength cross connect comprising: a first plurality of lenses stacked vertically; a second plurality of lenses stacked vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first
25 plurality of lenses; a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses; a second

plurality of dispersive elements, with one dispersive element substantially in a second focal plane of each of said second plurality of lenses; a first array of transmissive switching elements controllable in two directions, the first array being
5 substantially in a second focal plane of each of said first plurality of lenses; a second array of transmissive switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses; a first two dimensional array of optical
10 ports; a second two dimensional array of optical ports; for each row of said first two dimensional array of optical ports, a respective first bulk optical element having optical power and having a fourth focal plane substantially coplanar with said first focal plane of said second plurality of lenses; for
15 each row of said second two dimensional array of optical ports, a respective second bulk optical element having optical power and having a fifth focal plane substantially coplanar with said second focal plane of said first plurality of lenses; wherein each wavelength channel of a WDM signal entering at port of
20 said first array of optical ports is individually switchable to any of the port in first array of optical ports in a same row as the port where the WDM signal entered and any of the second array of optical ports through appropriate control of the array of switching elements.

25 In some embodiments, each bulk optical element a lens or a curved mirror.

 In some embodiments, the dispersive element is selected from a group comprising: a diffraction grating, either reflection and transmission type, prisms.

According to another broad aspect, the invention provides a wavelength cross connect comprising: a first plurality of lenses stacked vertically; a second plurality of lenses stacked vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first plurality of lenses; a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses; a second plurality of dispersive elements, with one dispersive element substantially in a second focal plane of each of said second plurality of lenses; a first array of transmissive switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses; a second array of transmissive switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses; a first two dimensional array of optical ports; a second two dimensional array of optical ports; a first bulk optical element having optical power and having a fourth focal plane substantially coplanar with said first focal plane of said second plurality of lenses; a second optical element having optical power and having a fifth focal plane substantially coplanar with said second focal plane of said first plurality of lenses; wherein each wavelength channel of a WDM signal entering at port of said first array of optical ports is individually switchable to any of the port in first array of optical ports in a same row as the port where the WDM signal entered and any of the second array of optical ports through appropriate control of the array of switching elements.

In some embodiments, each bulk optical element a lens or a curved mirror.

In some embodiments, the dispersive element is selected from a group comprising: a diffraction grating,
5 either reflection and transmission type, prisms.

According to another broad aspect, the invention provides an arrangement comprising: a first plurality of lenses stacked vertically; a second plurality of lenses stacked vertically, spaced from said first plurality of lenses, non-
10 overlapping in vertical space with said first plurality of lenses; a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses; a second plurality of dispersive elements, with one dispersive element substantially
15 in a second focal plane of each of said second plurality of lenses; a first array of switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses; a second array of switching elements controllable in two directions, the
20 second array being substantially in a first focal plane of each of said second plurality of lenses; a first plurality of two dimensional arrays of optical ports; a second plurality of two dimensional arrays of optical ports; for each two dimensional array of said first plurality of two dimensional arrays of
25 optical ports, a respective first bulk optical element having optical power and having a fourth focal plane substantially coplanar with said first focal plane of said second plurality of lenses; for each two dimensional array of said second

plurality of two dimensional arrays of optical ports, a respective second bulk optical element having optical power and having a fifth focal plane substantially coplanar with said second focal plane of said first plurality of lenses; wherein
5 each wavelength channel of a WDM signal entering at one of said first plurality of arrays of optical ports is individually switchable to any of the first plurality of arrays of optical ports and any of the second plurality of arrays of optical ports through appropriate control of the array of switching
10 elements.

In some embodiments, the switching elements are MEMS switching elements.

In some embodiments, the switching elements are transmissive.

15 In some embodiments, each bulk optical element is selected from a group consisting of a lens, a curved mirror, an assembly of lenses and mirrors, and an assembly of lenses, mirrors and a curved mirror.

20 In some embodiments, the second bulk optical element is selected from a group consisting of a lens, a curved mirror, an assembly of lenses and mirrors, and an assembly of lenses, mirrors and a curved mirror.

In some embodiments, the dispersive element is selected from a group comprising: a diffraction grating,
25 either reflection and transmission type, prisms.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows top and side views of a conventional wavelength switch configured as a 1x5 wavelength selective switch using free-space optics and MEMS switching elements;

5 Figure 2 shows top and side views of a ROADM with large number of add/drop ports configured as a 1x25 wavelength selective switch using free-space optics and MEMS switching elements;

10 Figure 3 shows a perspective view of the ROADM of Figure 2;

Figure 4 shows top and side views of a ROADM provided with a large number of add/drop ports configured as a 1x25 wavelength selective switch using waveguide optics and MEMS switching elements;

15 Figure 5 shows a wavelength cross-connect arrangement using free-space optics and MEMS switching elements, provided by an embodiment of the invention;

20 Figure 6A shows top and side views of a WXC/ROADM device provided by an embodiment of the invention using free-space optics and MEMS switching elements, in which each optical port has 5 local add/drop ports;

Figure 6B shows the add/drop/switch function of the device of Figure 6A;

18

Figure 7 shows a perspective view of the elements of the embodiment shown in figure 8;

Figure 8 shows top and side views of a WXC/ROADM device provided by an embodiment of the invention using
5 waveguide optics and MEMS switching elements, in which each optical port has 5 local add/drop ports;

Figure 9 shows top and side views of a WXC/ROADM provided by an embodiment of the invention with a large number of add/drop ports device using free-space optics and MEMS
10 switching elements, in which each optical port has 25 local add/drop ports;

Figure 10 shows top and side views of a WXC/ROADM provided by an embodiment of the invention with a large number of add/drop ports device using waveguide optics and MEMS
15 switching elements, in which each optical port has 25 local add/drop ports; and

Figure 11 shows top and side views of another embodiment of a WXC/ROADM device as per the invention using transmissive switching elements and waveguide optics, in which
20 each optical port has 5 local add/drop ports.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following detailed descriptions of Figures 1 to 11 are used to explain the mode of operation of the invention and describe the preferred embodiments as per the invention,
25 but should not be understood in narrow terms. Some of the

elements shown can be replaced by other realizations performing similar tasks. For example, wavelength dispersion can be realized through diffraction gratings (both reflection and transmission type) or prisms in free-space embodiments or through arrayed waveguide gratings or Echelle gratings in waveguide embodiments. Bulk optical elements having optical powers can be any of a lens, a curved mirror, or any suitable combination of optical elements, either spherical or cylindrical, that provide the appropriate optical function.

The array of switching means can be either reflective (mirrors, tunable gratings, interferometric arrangements of fixed and movable membranes, etc.), with the best mode being micro-mirror arrays fabricated through micro-fabrication processes, or transmissive (liquid crystal, electro-holograms, optical phase arrays, tiltable micro-prisms or movable micro-lenses, etc.). An example of a liquid crystal based switch is shown in: Patel et al., Photonics Technology Letters, Vol. 7, No. 5, May 1995. Waveguide and free space embodiments are possible to perform each of the dispersion and optical coupling steps, and any arbitrary appropriate combination can be employed. Although most of the descriptions will explain how to use arrangements as per the invention as a ROADM with multiple drop ports or ROADM/WXC with multiple drop ports, more generalization is possible without departing from the spirit of the invention.

For example, since light paths are bidirectional, drop ports can also be used as add ports or inputs for outputs. Furthermore, input or add and output or drop ports being essentially equivalent, their choice is arbitrary and should not limit the scope of the invention. Consistent choices will be made throughout the following for ease of description:

unless otherwise specified, the middle port in a group of ports is used as input/output, while the remaining ports in the group are used as add/drop ports. However, this is completely arbitrary.

5 In the following description of all figures except 3D perspective views (figures 3 and 7), the top part of each figure shows a top view, also referred to as the dispersion plane due to the choice of orientation of the dispersive elements, while the bottom part of the figure shows the side
10 view.

Figure 1 shows a known wavelength switch taught in D. M. Marom et al., Optical Fibre Communications conference, PD FB7, Anaheim, 2002. It is configured as a 1x5 with MEMS switching elements.

15 A group of 5 optical ports 10 is provided in the form of a linear array of optical fibres coupled to an array of micro-lenses 12 used to substantially collimate/focus the light beams from/to the optical fibres. In the cited reference, the middle fibre is used as an input port, while the 4 others are
20 used as outputs, although light paths going from the middle fibre back to the middle fibre are possible when used in conjunction with an optical circulator (thus the denomination as a 1x5 arrangement).

 In operation, a light beam containing multiple
25 wavelengths is input through the middle optical port, is collimated by the middle micro-lens and is directed to a diffraction grating 14 through a telescope arrangement

consisting of a coupling lens 16 and a main lens 18. After reflecting from the diffraction grating 14, the light beam is demultiplexed into a plurality of wavelength channels, each impinging on a corresponding MEMS switch element 20. This MEMS
5 can tilt in the plane of the dispersion to route the wavelength channels to alternate locations on the diffraction grating 14. The images of these alternate locations through the telescope can be made to precisely align to one of the micro-lens, thus the wavelength channels is made to couple to a selectable
10 optical port.

As is known to a person skilled in the art, off-axis aberrations in any optical system worsen dramatically as the field of view is increased. This is all the more true when the optical system is already working off-axis, which is the case
15 in the dispersion plane because of the physical extent of the MEMS array 20. In the cited reference, increasing the number of optical ports would mean a bigger image for the telescope, and thus a bigger field of view for the main lens in particular. Therefore, the wavelength switch as per the prior
20 art is limited to a small number of optical ports. Typically, no more than 8 ports can be arranged in such an optical system without generating excessive penalty in either optical performance (mainly insertion loss uniformity over wavelength) or size.

25 Figure 2 shows a wavelength switch providing a large number of optical ports that can be used for example as a ROADM with a large number of add/drop ports. In the example shown on Figure 2, the wavelength switch can be configured as a 1x25.

This is a variant of a system taught in U.S. patent no. 6,549,699 to Belser et al.

This dramatic increase in scalability in number of ports is achieved by using a two dimensional arrangement of optical ports consisting of a two dimensional array of fibres 30 connected to a two dimensional array of micro-lenses 32 to substantially collimate/focus light beams as they emerged/are coupled to the optical fibres and by using an array of MEMS switching elements 34 capable of directing light beams in both the plane of dispersion and the plane perpendicular to the plane of dispersion. In the example shown in Figure 2, the ports are arranged in a 5x5 array, enabling one input and 25 potential outputs, thus the 1x25 naming (counting the path from the input back to itself as one possible path, although requiring an external circulator).

In operation, a light beam containing multiple wavelengths is input through the middle optical port, is collimated by the middle micro-lens and is directed to the diffraction through a telescope arrangement consisting of a coupling lens 36 and a main lens 38. After reflecting from a diffraction grating, the light beam is demultiplexed into a plurality of wavelength channels, each impinging on a corresponding MEMS switch element 34. This MEMS can tilt both in the plane of the dispersion and in the plane perpendicular to the dispersion plane to route the wavelength channels to alternate locations on the diffraction grating 40. The images of these alternate locations through the telescope can be made to precisely align to one of the micro-lens of the two

dimensional array 32, thus each wavelength channel is made to couple to a selectable optical port.

Throughout this description, a wavelength channel is an arbitrary contiguous frequency band. A single wavelength
5 channel might include one or more ITU wavelengths and intervening wavelengths for example. Even though the expression " λ " is referred to herein in respect of a wavelength channel, this is not intended to imply a wavelength channel is a single wavelength only.

10 By using a two dimensional arrangements of optical ports, the image formed on the grating 40 containing all possible alternate locations is small both in the dispersion plane and in the plane perpendicular to the dispersion plane. Compared to a prior art implementation as described in Figure 1
15 expanded to include the same number of ports, the width of the image in the plane of dispersion would be reduced by a factor of 6, which has a dramatic impact on optical performances of the system. The larger size of the embodiment as per the invention in the plane perpendicular to the dispersion plane
20 has a small negative impact since the system remains mostly on-axis in that plane.

Therefore, assuming that 8 ports was the practical limitations imposed by optical design on an implementation as per the prior art, the two dimensional arrangement of optical
25 ports provided by the invention would enable building a device of up to 1x64 ports or with a smaller number of ports but with improved optical performances and smaller size. These

numerical values are for the purpose of explaining the improvement over the Figure 1 arrangement. Other numbers of ports are possible.

5 Figure 3 shows a perspective view. The two dimensional arrangement of ports and corresponding micro-lenses is clearly visible on this drawing.

 Figures 4A and 4B illustrate another embodiment
10 performing a similar function that the device shown on Figure 3, but using waveguide based dispersive elements.

 This waveguide based dispersive element and the associated coupling optics necessary to use it are described
15 in applicants co-pending applications 60/381,364 filed on May 20, 2003 and issued on June 26, 2007 as United States Patent No.7,236,660.

 The stacked arrangement of FIGS. 4A and 4B include
20 a respective waveguide device 504A through 504E for each layer. Layers 504A, 504B, 504D and 504E have respective sets of output ports. The output ports of device 504A are ports 501Aa through to 501Ae. Similarly the output ports of device 504E are ports 501Ea through to 501Ee. The waveguide device
25 504C also has an input port. The input port for device 504C is port 501Cc. The remaining ports 501Ca, 501Cb, 501Cd and 501Ce of device 501C are output ports. Thus, there is an array of 25 ports, one of which is an input port (501Cc) and 24 of which are output ports. This is an example
30 configuration used for description of the invention. Other combinations of input and output ports are possible without departing from the spirit of the

invention. In the illustrated embodiment, there is one input port and the remaining ports are output ports. In another embodiment, all of the ports are input ports except one, which is an output port. In yet another embodiment, there are multiple input ports and multiple output ports. This last arrangement is not fully non-blocking. The arrangement 500 further includes for each waveguide device 504A through 504E a respective cylindrical lens 506A through 506E. There is also provided a single bulk optical element 508. There is an array of switching elements 509 shown most clearly in the view of FIG. 4A, each of which are capable of tilting in two dimensions, including tilting in the plane of FIG. 4A, and tilting in the plane of FIG. 4B. Tilting in the plane of 5A allows switching between different ports of the same device 504A to 504E and tilting in the plane of FIG. 4B allows switching between ports of different waveguide devices.

Each of the ports (both input and output) are coupled to a respective integrated coupling optics on one of the devices 504A through 504E. For example, output port 501Aa is coupled to integrated coupling optics 502Aa. It is noted that the embodiment of FIG. 4A could be implemented using optical elements instead of using the integrated optics as shown in the illustrated example.

25

By way of example, a DWDM light beam containing wavelengths λ_1 to λ_5 is shown input into the multi-ROADM device 500 at input port 501Cc. It is coupled to a waveguide dispersive element 505Cc of waveguide device 504C through integrated coupling optics 502Cc. The waveguide dispersive element consists of an array of waveguides

30

having a predetermined optical length difference causing a wavelength dependent exit angle of the light upon exit of the waveguide device 504C. Therefore, the light is demultiplexed in 5 beams comprising respectively λ_1 to λ_5 referenced 507-1 to 507-5. On FIG. 4A, only beams 507-2 to 507-4 are shown for clarity. Those beams are substantially collimated in the plane perpendicular to the plane of the figure upon traversing cylindrical lens 506C, while being-virtually unaffected in the plane of the figure. The main cylindrical lens 508 is used to route each beam 507-1 to 507-5 to a corresponding switching element 509-1 to 509-5, while virtually not impacting light propagation in the plane perpendicular to the plane of the figure. Those switching elements preferably consist of an array of tiltable mirrors capable of tilting both in the plane of the figure and in the perpendicular plane. When the mirrors are tilted in the plane of the figure, the light beams 507 can be routed to a particular horizontal location a to e. When the mirrors are tilted in the perpendicular plane, the light beams 507 can be routed to a particular waveguide device 504A to 504E in the waveguide stack 504. Therefore, an appropriate combination of tilt in the plane of the figure and perpendicular to the plane of the figure enables to route each beam 507-1 to 507-5 to any of the 25 possible waveguide dispersive elements 505Aa to 505Ee. In a preferred embodiment, the main cylindrical lens 508 is placed in-between the waveguide stack 504 and switching array 509 such that both the waveguide stack 504 and the switching array 509 lie in the vicinity of the focal plane of cylindrical lens 508. This arrangement guarantees that irrespective of the tilt of the MEMS mirrors 509-1 to 509-5, light beams 507-1 to 507-5 will always have an incident

angle in the plane of the figure into any of the waveguide dispersive elements 505Aa to 505Ee that maximizes the coupling (i.e. the incident angle is substantially the same as the angle upon exit of the input waveguide dispersive element 505Cc).

The array of cylindrical lenses 506A to 506E is used to refocus and steer the light beams 507-1 to 507-5 to their respective waveguide device 504A to 504E depending on the switching pattern. In the case of the FIGS. 4A and 4B, λ_3 has been arbitrarily switched from waveguide dispersive element 505Cc to waveguide dispersive element 505Aa, λ_4 has been switched from 505Cc to 505Ee and λ_2 has been switched from 505Cc to 505Cb. After being coupled to their respective waveguide dispersive element 505, the light beams 507 are brought to their respective optical ports 501 through integrated coupling elements 502. In the particular case of the figure, the 3 depicted wavelengths λ_2 to λ_4 exit at respectively optical ports 501Cb, 501Aa, and 501Ee.

20

Referring again to FIG. 4B an important point on this figure is the arrangement of the array of cylindrical lenses 506A to 506E used to substantially collimate light beams 507-1 to 507-5 exiting from the waveguide dispersive element 505Cc in the plane of the figure, while not affecting light propagation in the perpendicular plane and used to substantially re-focus light beams 507-1 to 507-5 when they re-enter their respective waveguide dispersive element 505Aa to 505Ee depending on their switching pattern. The optical centre of cylindrical lenses 506A to 506E are aligned such that a 0 degree angle of incidence to the waveguide devices 504A to 504E is obtained when the

30

switching mirrors 509 are tilting in the plane of FIG. 4B. For the particular embodiment depicted on FIGS. 4A and 4B, this is done by offsetting the centre of cylindrical lenses 506A, 506B, 506D and 506E by an appropriate amount.

5

Figure 5 shows a wavelength cross-connect arrangement using free-space optics and MEMS switching elements provided by an embodiment of the invention. It basically consists of a first stack 54, 56, 58, 60 and a
10 second stack 62, 64, 66, 68 of dispersive arrangements connected together via optical paths established by MEMS micro-mirrors capable of tilting in the plane perpendicular to the dispersion plane. More specifically, referring to the bottom view of Figure 5, there are four input ports 42, 43,
15 44, 45 and four output ports 46, 47, 48, 49. This designation between input and output is arbitrary, and any port can function as either input or output. Each input port 42, 43, 44, 45 has a respective main lens

80,82,84,86 through which light travels on the way to a respective diffraction grating 62,64,66,68. Each diffraction grating 62,64,66,68 redirects light back through the respective main lens 80,82,84,86 to a respective array of MEMS micro-
5 mirrors 88,90,92,94. Each array of MEMS micro-mirrors, for example array 88 shown in the top view, includes a series of micro-mirrors arranged in a line perpendicular to the view in the bottom of Figure 5. Also shown is a second set of micro-mirror arrays 96,98,100,102 each of which directs light through
10 a respective main lens 70,72,74,76 to a respective diffraction grating 54,56,58,60. The diffraction gratings 54,56,58,60 redirect light back through the main lens 70,72,74,76 and through output ports 46,47,48,49. The top view of Figure 5 shows functionality for input port 42 and output port 46. Each
15 port might include associated beam forming optics if necessary, this being illustrated by the rectangles in the figure. This might for example consist of being expanders/reducers, either spherical or anamorphic.

The arrangement of Figure 5 allows any wavelength or
20 combination of wavelengths received on any input port to be routed to any of the output ports. It is noted that in this embodiment, the micro-mirrors in arrays 88,90,92,94 only tilt in one plane. And as such light is always reflected from one micro-mirror of one of the first arrays 88,90,92,94 to a
25 corresponding micro-mirror in one of the second arrays 96,98,100,102. An example of this is shown in the top view of Figure 5 where input port functionality is shown in respect of the first input port 42, and output port functionality is shown in respect of the first output port 46. The route travelled by

a single wavelength is indicated generally at 108. A signal comes in through input port 42, and this passes through the first port's main lens 80 to the first port's diffraction grating 62. This performs a wavelength dependent redirection
5 back through the main lens 80 to one of the micro-mirrors of the first input port's micro-mirror array 88. Specifically, light is directed onto micro-mirror 104 forming part of micro-mirror array 88. In the illustrated example, it is assumed that this is the first micro-mirror of array 88. This is
10 reflected to a corresponding micro-mirror in micro-mirror array 96, and in particular the first micro-mirror 106. Micro-mirror 106 reflects the light through the first output port's main lens 70 to the first output port's diffraction grating 54 which performs a wavelength dependent redirection back through main
15 lens 70 and through the output port 46.

In the example shown in Figure 5, each stack contains four dispersive arrangements. One dispersive arrangement of each stack is shown in the top view. The four dispersive arrangements are aligned on top of each other as indicated in
20 the figure. The two stacks are positioned one on the left and one on the right hand side such that the MEMS mirrors from the first stack can establish an optical path to the MEMS mirrors in the second stack and vice-versa in at least the plane perpendicular to the dispersion plane.

25 In operation, four light beams containing a plurality of wavelength channels are input to the WXC on the four input ports 42,44,46,48 (arbitrarily chosen as the left hand side top fibre stack in the figure). The four light beams travel

through their respective main lens 80,82,84,86 to their respective diffraction grating 62,64,66,68 where they get demultiplexed into a respective plurality of wavelength channels. Each respective plurality of wavelength channels is
5 routed to a corresponding first MEMS micro-mirror (one micro-mirror per input port and per wavelength channel) in the respective array 88,90,92,94 through their respective main lens 80,82,84,86. These MEMS micro-mirrors can establish an optical path to second MEMS micro-mirrors in arrays 96,98,100,102 of
10 the second stack of dispersive arrangements. Each micro-mirror of the arrays 96,98,100,102 is then tilted such that each wavelength channel from each light beam is routed through their corresponding second main lens 70,72,76,78 to their corresponding second diffraction grating 54,56,58,60 where they
15 get remultiplexed into four respective light beams. These four respective light beams are routed to the output optical ports 46,47,48,49 through their respective second main lens 70,72,74,76.

Another embodiment as per the invention but not shown
20 uses transmissive switching means instead of MEMS micro-mirror arrays 88, 90, 92, 94, 96, 98, 100, 102. The embodiment would look like the below described Figure 11 embodiment, but with only one part in the top view of Figure 11, and multiple parts in the bottom view.

25 In another embodiment, the embodiment of Figure 5 is implemented using waveguide dispersive elements. The embodiment would look like the embodiment of Figure 8 described

below, but with only a single part on each side in the top view, and multiple parts in the bottom view.

Figure 6A shows an integrated WXC/ROADM device provided by an embodiment of the invention using free-space optics and MEMS switching elements, in which each ROADM has 5 local add/drop ports. This embodiment is similar to that of Figure 5, but in this embodiment, to provide this added functionality, the optical ports are now grouped in a first two dimensional array of ports 120 and a second two dimensional array of ports 122. More specifically, the input array of ports in the illustrated example consists of an array of four rows of five ports. The 4x5 array of input ports 120 has an associated micro-lens 124 for each input port, and each column of ports has a respective collimating lens 126. Similar coupling optics are provided at the output port 122. The one dimensional tilting micro-mirror arrays 88,90,92,94,96,98,100,102 of Figure 5 are replaced with arrays 121,123,125,127,128,130,132,134 of micro-mirrors which are capable of tilting both in the plane of dispersion and in the perpendicular plane to the dispersion plane. For ease of description of this figure, row refers to the dispersion plane, while column refers to the plane perpendicular to the dispersion plane.

In the plane perpendicular to the dispersion plane, the integrated WXC/ROADM looks similar to a simple WXC (like figure 5), with the exception of a slightly more complex coupling optics. In the dispersion plane, however, there are multiple optical ports provided per dispersive arrangement

compared to only one in the embodiment of Figure 5. These added ports can be used for example as local add/drop ports, although other uses are possible without departing from the spirit of the invention. Arbitrarily, the middle optical ports of each row of ports are chosen as an input/output ports, while the other ports are chosen as add/drop ports.

In operation, four light beams containing a plurality of wavelength channels are input to the WXC on the four input ports of the input group (arbitrarily chosen as the left hand side top fibre stack in the side view figure, middle column of the two dimensional array of optical ports). The four light beams are collimated by their respective micro-lenses corresponding to the middle column of the two dimensional micro-lens array and input to their respective dispersive arrangement. The four light beams travel through their respective main lens to their respective diffraction grating where they get demultiplexed into a respective plurality of wavelength channels. Each respective plurality of wavelength channels is routed to a corresponding first MEMS micro-mirror (one micro-mirror per input port and per wavelength channel) through their respective main lens. These MEMS micro-mirrors can establish an optical path to second MEMS micro-mirrors of the second stack of dispersive arrangements or send the light back towards their respective first dispersive arrangement.

For the beams being routed to these second MEMS elements, these second MEMS micro-mirrors are tilted such that each wavelength channel from each light beam is routed through their corresponding second main lens to their corresponding

second diffraction grating where they get remultiplexed into four respective light beams. These four respective light beams are routed to the output optical ports through their respective second main lens.

5 For the beams being routed back towards their respective first dispersive arrangement, their corresponding first MEMS micro-mirror can be tilted in the dispersion plane to route the corresponding wavelength channel to alternate locations on their respective diffraction grating. As
10 explained in the description of Figure 1, this alternate location is imaged to an alternate location in their respective micro-lens array row, corresponding to a tuneable add/drop port.

 Therefore, a function of simultaneously WXC (for the
15 beams bouncing off first MEMS and second MEMS) and add/drop (for the beams bouncing off only first MEMS) is provided in a single device.

 Figure 6B is a diagram showing the add/drop/switch functionality of the embodiment of Figure 6A. For the
20 embodiment of 6B, port 2000 is an arbitrary port from the left hand array of ports 120, and port 2006 is an arbitrary port from the right hand array of ports 122. Light is shown entering the port 2000. A wavelength channel dependent switching function is realized as indicated generally at 2002.
25 Through appropriate selection of the angle of the switching elements, any wavelength channel can be returned to a port in the same row as input port 2000. Drop ports 2008, 2010, 2012,

2014 are shown, functioning as the drop ports in the same row as input port 2000. Any wavelength channel in the input signal can be routed back to any of these drop ports. Similarly, any wavelength channel can be routed to a second switching element
5 generally indicated at 2004. Note the first switching element 2002 belongs to array 129 while the second switching element 2004 belongs to array 128. A similar functionality is achieved at the output port 2006. Namely, any other port in the same row as the output port 2006 can function as an add port. Ports
10 2016, 2018, 2020, 2022 are shown in the figure functioning as add ports. A wavelength channel can be input to any of these add ports and will be added to the output signal at port 2006. Thus, with one bounce off the switching element, local drops at the input can be achieved and local drops at the output can be
15 achieved with two bounces off the two sets of switching elements, a switching function from an input port to any of the output ports is achieved.

In another embodiment the tilt in the dispersion plane is provided with the second MEMS, not the first one,
20 yielding different possible application.

In yet another embodiment as per the invention, the tilt is provided by either the first MEMS or the second MEMS depending on wavelength channels.

Figure 7 shows a perspective view of the elements of
25 the embodiment described in Figure 8 of an integrated WXC/ROADM using waveguide and MEMS configured as a 5x5 WXC wherein each optical port can have 5 local add/drop paths (again counting

the case of the light being directed from the input back to itself as a possible local add/drop path with the use of an external circulator).

Figure 8 shows a preferred embodiment as per the invention in which waveguide dispersive elements are used in conjunction with MEMS based arrays of switching means to realize an integrated ROADM/WXC device with 5x5 wavelength cross-connect capacity and 1x5 local add/drop capability on each of the 5 incoming and 5 out coming ports.

This arrangement consists of a first two dimensional array of waveguide based dispersive elements. These are realized through a stack of single dimensional arrays 200,204,206,208,210 each of which contains five waveguide dispersive elements. The waveguide dispersive elements 290,292,294,296,298 of array 200 are shown in the perspective view of Figure 7. Each array 200,204,206,208,210 has a respective cylindrical lens 212,214,216,218,220 to collimate/focus light beams emitted/received by the waveguide dispersive elements in the plane perpendicular to the waveguide substrate. Each waveguide device of the stack is further coupled to respective main cylindrical lens 222,224,226,228,230. The main cylindrical lens is used to focus/collimate light beams emitted/received by the waveguide dispersive element in the waveguide substrate's plane. The arrangement further comprises a first stack of switching elements 274 which is a two dimensional array of MEMS micro-mirrors capable of tilting in two dimensions. Although MEMS micro-mirrors are depicted in the figure, alternative switching

elements can also be used as mentioned previously. There is a second two dimensional array of micro-mirrors 272 which redirects light received from the first two dimensional array of micro-mirrors 274 through a second set of main cylindrical lenses 232,234,236,238,240. There is a second stack of arrays of waveguide dispersive elements 260,262,264,268,270 with respective collimating lenses 242,246,248,250,252 aligned with cylindrical lenses 232,234,236,238,240.

The different elements are arranged such that if a light beam containing a plurality of wavelength channels is input into one of the optical ports of the first stack of waveguide devices, it is dispersed by its respective waveguide dispersive elements into a plurality of light beams each containing a wavelength channel. These light beams are routed through the respective cylindrical lens and main cylindrical lens to a corresponding switching element (there is one switching element per wavelength channel per waveguide device in a stack). These switching elements can either send the light back towards their incoming waveguide device in the first stack, providing local add/drop ports or send the light towards a corresponding second switching element of the second stack of array of switching elements. These second switching elements can route the beams towards any of the optical ports of the corresponding waveguide device in the second stack.

Although in the figure there is provided a first array of main cylindrical lenses and a second array of main cylindrical lenses, it is apparent to a man skilled in the art that each of the lenses of the first and second array can be

replaced by a single first and single second bigger main cylindrical lenses. The embodiment featuring the bigger main cylindrical lenses is shown in the perspective view of Figure 7 whereas the embodiment showing arrays of main cylindrical
5 lenses is shown in the views of Figure 8.

Figure 9 shows another embodiment of the invention of an integrated WXC/ROADM, in which the ROADM has a large number of ports based on MEMS + free space. This results from a two dimensional arrangement of add/drop ports for each of the
10 dispersive arrangements. There is a similar increase in number of add/drop ports going from the embodiment in Figure 1 to the embodiment in Figure 2 for a wavelength switch as going from the embodiment in Figure 6 to the embodiment in Figure 9 for a wavelength cross-connect.

15 The WXC/ROADM with large number of add/drop ports as per the invention consists of a first stack 900 and a second stack 902 of wavelength switch elements.

In what follows, only one element of each type of wavelength switch element is labelled.

20 Each wavelength switch element comprises a two dimensional arrangement of optical ports 904 coupled through a first lens 906 and a main lens 908 to a diffraction grating 910 and an array of switching elements 912. When a light beam containing a plurality of wavelength channels is coupled to any
25 of the optical ports, it is dispersed by the diffraction grating into a plurality of optical beams each containing one wavelength channel. These optical beams are routed to a

switching element of the switching array. The wavelength switch is arranged such that there is a fixed correspondence between the wavelength channel and the switching element for all possible optical ports. This is for example possible when
5 the diffraction grating and the array of switching elements lie substantially in the focal planes of the main lens.

The two stacks of wavelength switch elements are arranged such that the switching elements of the first stack of wavelength switches can establish an optical path back to the
10 corresponding wavelength switch of the first stack or to any other wavelength switch in the second stack and such that the switching elements of the second stack of wavelength switches can establish an optical path back to the corresponding
wavelength switch of the second stack or to any other
15 wavelength switch in the first stack.

In operation, a plurality of optical paths can be established through the WXC/ROADM device in which light can be routed from any optical ports of any of the wavelength switch from the first stack to any of the optical ports of the
20 corresponding wavelength switch for local add/drop or routed to any of the optical ports of any of the wavelength switches from the second stack.

In the Figure, an example path is shown going from the middle port (3rd row and 3rd column) of the first of the
25 left group of 2D arrangements of ports to the fourth row and fifth column of the first of the left group of the 2D arrangement of ports (black line turning into light grey line)

and another example path is shown from the middle ports of the first of the left group of 2D arrangements of ports to the middle port of the third of the right group of 2D arrangement of ports.

5 Figure 10 shows a WG embodiment of the invention shown in figure 9 to provide an integrated WXC/ROADM with a large number of add/drop ports. This embodiment is similar to that of Figure 9 with the ports and diffraction gratings replaced with waveguide dispersive elements.

10 The device consists of a first group 1000 and a second group 1002 of stacks of waveguide devices. Each waveguide device comprises an array of at least one waveguide based dispersive element. For each stack of waveguide device e.g. stack 1004, there is provided an array of switching
15 elements 1010. For each waveguide device in each stack e.g. device 1006 of stack 1004, there is a corresponding cylindrical lens 1008 to collimate/focus light beams emitted/received from the waveguide device in the plane of the waveguide substrate and to create an optical path from the waveguide device to the
20 array of switching elements corresponding to their stack. For each waveguide device, there is further provided a corresponding main cylindrical lens 1020 to focus/collimate light beams emitted/received from the waveguide device in the dispersion plane. These main cylindrical lenses can be
25 replaced by a single bigger main cylindrical lens for each waveguide device or for each stack.

The first switching elements 1010 are arranged such that an optical path can be established from any of the optical ports of any waveguide device of any stacks of the first group 1000 to either any of the optical ports of any waveguide device
5 in the same stack of the first group 1000 or to any of the optical ports of any waveguide device of any stacks of the second group 1002. The second switching elements 1012 are arranged such that an optical path can be established from any of the optical ports of any waveguide device of any stacks of
10 the second group 1002 to either any of the optical ports of any waveguide device in the same stack of the second group 1002 or to any of the optical ports of any waveguide device of any stacks of the first group 1000.

Figure 11 shows an alternate embodiment as per the
15 invention similar in functionality and mode of operation to figure 6 in which the first 1100 and second array 1102 of switching means are transmissive beam steering elements.

Figure 12 shows an alternate embodiment as per the invention similar in functionality and mode of operation to
20 figure 8 in which the first 1200 and second array 1202 of switching means are transmissive beam steering elements.

The embodiments featuring waveguide dispersive elements are shown to include integrated port coupling optics. Alternatively, the coupling optics can be realized with
25 separate micro-optics coupling schemes.

The invention is not intended to be limited to the above mentioned specific embodiments but should rather be understood as being within the scope of the appended claims.

CLAIMS:

1. A wavelength cross connect comprising:

a first plurality of lenses stacked

vertically;

5 a second plurality of lenses stacked

vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first plurality of lenses;

10 a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses;

a second plurality of dispersive elements, with one dispersive element substantially in a second focal plane of each of said second plurality of lenses;

15 a first array of switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses;

20 a second array of switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses;

25 in a first plurality of optical ports a respective optical port positioned to input light onto/receive light from each of said first plurality of lenses;

30 in a second plurality of optical ports a respective optical port positioned to input light onto/receive light from each of said second plurality of lenses;

40

wherein light entering any of said first plurality of optical ports or said second plurality of ports is switchable to any of the first plurality of optical ports and any of said second plurality of optical ports.

5

2. The wavelength cross connect according to claim 1, wherein the first array of switching elements comprise MEMS switching elements.

10 3. The wavelength cross connect according to claim 1 or 2, wherein the second array of switching elements comprise MEMS switching elements.

4. A wavelength cross connect according to claim
15 1, 2 or 3, wherein each first bulk optical element is selected from a group consisting of a lens or a curved mirror.

5. A wavelength cross connect according to any
20 one of claims 1 to 4, wherein each of the first dispersive elements is selected from a group consisting of: a diffraction grating, either reflection and transmission type, and prisms.

25 6. A wavelength cross connect according to any one of claims 1 to 5, wherein each of the second dispersive elements is selected from a group consisting of: a diffraction grating, either reflection and transmission type, and prisms.

30

7. The wavelength cross connect according to any

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one of claims 1 to 4, wherein the first plurality of dispersive elements comprise alternate locations on a diffraction grating.

5 8. The wavelength cross connect according to any one of claims 1 to 5, wherein the second plurality of dispersive elements comprise alternate locations on a diffraction grating.

10 9. The wavelength cross connect according to any one of claims 1 to 8, wherein the first array of switching elements comprises transmissive switching elements.

10. The wavelength cross connect according to
15 claim 9, wherein each of the transmissive switching elements in the first array of switching elements is selected from the group consisting of a liquid crystal beam steering element, an acousto-optic beam deflector, part of a solid
20 state phase array, a controllable hologram, and a periodically poled Lithium Niobate beam deflector.

11. The wavelength cross connect according to any one of claims 1 to 10, wherein the second array of switching elements comprises transmissive switching elements.

25

12. The wavelength cross connect according to claim 11, wherein each of the transmissive switching elements in the second array of switching elements is selected from the group consisting of a liquid crystal beam
30 steering element, an acousto-optic beam deflector, part of a solid state phase array, a controllable hologram, and a

periodically poled Lithium Niobate beam deflector.

13. A wavelength cross connect comprising:

a first plurality of lenses stacked

5 vertically;

a second plurality of lenses stacked

vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first plurality of lenses;

10 a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses;

a second plurality of dispersive elements, with one dispersive element substantially in a second focal plane of each of said second plurality of lenses;

15 a first array of switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses;

20 a second array of switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses;

25 a first two dimensional array of optical ports;

a second two dimensional array of optical ports;

30 for each row of said first two dimensional array of optical ports, a respective first bulk optical element having optical power and having a fourth focal plane

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substantially coplanar with said first focal plane of said second plurality of lenses;

for each row of said second two dimensional array of optical ports, a respective second bulk optical element having optical power and having a fifth focal plane substantially coplanar with said second focal plane of said first plurality of lenses;

wherein each wavelength channel of a WDM signal entering at a port of said first array of optical ports is individually switchable to any of the port in first array of optical ports in a same row as the port where the WDM signal entered and any of the second array of optical ports through appropriate control of the array of switching elements.

15

14. The wavelength cross connect according to claim 13, wherein each of the first and second arrays of switching elements comprises MEMS switching elements.

20 15. The wavelength cross connect according to claim 13 or 14, wherein each of the first and second bulk optical element comprise a lens or a curved mirror.

16. The wavelength cross connect according to claim 13, 14 or 15, wherein each of the first and second plurality of dispersive elements comprises diffraction gratings, either reflection and transmission type, or prisms.

30 17. A wavelength cross connect comprising:

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a first plurality of lenses stacked vertically;

a second plurality of lenses stacked vertically, spaced from said first plurality of lenses, non-
5 overlapping in vertical space with said first plurality of lenses;

a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses;

10 a second plurality of dispersive elements, with one dispersive element substantially in a second focal plane of each of said second plurality of lenses;

a first array of switching elements controllable in two directions, the first array being
15 substantially in a second focal plane of each of said first plurality of lenses;

a second array of switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second
20 plurality of lenses; a first two dimensional array of optical ports;

a second two dimensional array of optical ports;

a first bulk optical element having optical
25 power and having a fourth focal plane substantially coplanar with said first focal plane of said second plurality of lenses;

a second bulk optical element having optical power and having a fifth focal plane substantially coplanar
30 with said second focal plane of said first plurality of lenses;

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wherein each wavelength channel of a WDM signal entering at a port of said first array of optical ports is individually switchable to any of the port in first array of optical ports in a same row as the port where the WDM signal entered and any of the second array of optical ports through appropriate control of the array of switching elements.

18. The wavelength cross connect according to claim 17, wherein each of the first and second arrays of switching elements comprises MEMS switching elements.

19. The wavelength cross connect according to claim 17 or 18, wherein each of the first and second bulk optical elements comprises a lens or a curved mirror.

20. The wavelength cross connect according to claim 17, 18 or 19, wherein each of the first and second plurality of dispersive elements comprises diffraction gratings, either reflection and transmission type, or prisms.

21. An arrangement comprising:
a first two dimensional array of optical ports;
a first two dimensional array of waveguide dispersive elements on a plurality of waveguide substrates, with one waveguide dispersive element per optical port in said first two dimensional array of optical ports, the first two dimensional array of waveguide dispersive elements collectively having a first output plane;

46

for each row of said first two dimensional array of optical ports, a respective first bulk optical element having optical power and having a first focal plane substantially coplanar with said first output plane, and
5 having a second focal plane;

a first array of switching elements substantially in the second focal plane, each switching element being adapted to switch in both a horizontal and vertical direction;

10 a second two dimensional array of optical ports;

a second two dimensional array of waveguide dispersive elements on a plurality of waveguide substrates, with one waveguide dispersive element per optical port in
15 said second two dimensional array of optical ports, the second two dimensional array of waveguide dispersive elements collectively having a second output plane;

for each row of said second two dimensional array of optical ports, a respective second bulk optical
20 element having optical power and having a fifth focal plane and having a sixth focal plane substantially coplanar with the second output plane;

a second array of switching elements substantially in the fifth focal plane, each switching
25 element being adapted to switch in both a horizontal and vertical direction;

wherein each wavelength channel of a WDM signal entering at one of said first array of optical ports is individually switchable to any of the optical ports of
30 the first array in a same row as the port through which the signal entered and any of the optical ports of the second

47

array through appropriate control of the array of switching elements

22. The arrangement according to claim 21, wherein
5 each of the first and second arrays of switching elements comprise MEMS switching elements.

23. The arrangement according to claim 21 or 22,
wherein each of the first and second bulk optical elements
10 having optical power comprises a lens or a curved mirror.

24. The arrangement according to claim 21, 22 or
23, wherein each of the first and second arrays of
dispersive elements comprises arrayed waveguide gratings or
15 Echelle gratings.

25. An arrangement comprising:

a first two dimensional array of optical
ports;

a first two dimensional array of waveguide
20 dispersive elements on a plurality of waveguide substrates,
with one waveguide dispersive element per optical port in
said first two dimensional array of optical ports, the first
two dimensional array of waveguide dispersive elements
collectively having a first output plane;

25 a first bulk optical element having optical
power and having a first focal plane substantially coplanar
with said first output plane, and having a second focal
plane;

a first array of switching elements
30 substantially in the second focal plane, each switching

48

element being adapted to switch in both a horizontal and vertical direction;

a second two dimensional array of optical ports;

5 a second two dimensional array of waveguide dispersive elements on a plurality of waveguide substrates, with one waveguide dispersive element per optical port in said second two dimensional array of optical ports, the second two dimensional array of waveguide dispersive
10 elements collectively having a second output plane;

a second bulk optical element having optical power and having a fifth focal plane substantially coplanar with the second output plane;

a second array of switching elements
15 substantially in the fifth focal plane, each switching element being adapted to switch in both a horizontal and vertical direction;

wherein each wavelength channel of a WDM signal entering at one of said first array of optical ports
20 is individually switchable to any of the optical ports of the first array in a same row as the port through which the signal entered and any of the optical ports of the second array through appropriate control of the array of switching elements.

25

26. The arrangement according to claim 25, wherein each of the first and second arrays of switching elements comprises MEMS switching elements.

30

27. The arrangement according to claim 25 or 26, wherein each of the first and second bulk optical elements

49

having optical power comprises a lens or a curved mirror.

28. The arrangement according to claim 25, 26 or 27, wherein each of the first and second arrays of
5 dispersive elements comprises arrayed waveguide gratings or Echelle gratings.

29. A wavelength cross connect comprising:
 a first plurality of lenses stacked
10 vertically;
 a second plurality of lenses stacked
vertically, spaced from said first plurality of lenses, non-
overlapping in vertical space with said first plurality of
lenses;
15 a first plurality of dispersive elements, with
one dispersive element substantially in a first focal plane
of each of said first plurality of lenses;
 a second plurality of dispersive elements,
with one dispersive element substantially in a second focal
20 plane of each of said second plurality of lenses;
 a first array of transmissive switching
elements controllable in two directions, the first array
being substantially in a second focal plane of each of said
first plurality of lenses;
25 a second array of transmissive switching
elements controllable in two directions, the second array
being substantially in a first focal plane of each of said
second plurality of lenses;
 a first two dimensional array of optical
30 ports;

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a second two dimensional array of optical ports;

for each row of said first two dimensional array of optical ports, a respective first bulk optical element having optical power and having a fourth focal plane substantially coplanar with said first focal plane of said second plurality of lenses;

for each row of said second two dimensional array of optical ports, a respective second bulk optical element having optical power and having a fifth focal plane substantially coplanar with said second focal plane of said first plurality of lenses;

wherein each wavelength channel of a WDM signal entering at port of said first array of optical ports is individually switchable to any of the port in first array of optical ports in a same row as the port where the WDM signal entered and any of the second array of optical ports through appropriate control of the array of switching elements.

20

30. The wavelength cross connect according to claim 29, wherein each of the first and second bulk optical elements comprise a lens or a curved mirror.

25

31. The wavelength cross connect according to claim 29 or 30, wherein each of the first and second plurality of dispersive elements comprise diffraction gratings, either reflection and transmission type, or prisms.

30

32. A wavelength cross connect comprising:

51

a first plurality of lenses stacked
vertically;

a second plurality of lenses stacked
vertically, spaced from said first plurality of lenses, non-
5 overlapping in vertical space with said first plurality of
lenses;

a first plurality of dispersive elements, with
one dispersive element substantially in a first focal plane
of each of said first plurality of lenses;

10 a second plurality of dispersive elements,
with one dispersive element substantially in a second focal
plane of each of said second plurality of lenses;

a first array of transmissive switching
elements controllable in two directions, the first array
15 being substantially in a second focal plane of each of said
first plurality of lenses;

a second array of transmissive switching
elements controllable in two directions, the second array
being substantially in a first focal plane of each of said
20 second plurality of lenses; a first two dimensional array of
optical ports;

a second two dimensional array of optical
ports;

a first bulk optical element having optical
25 power and having a fourth focal plane substantially coplanar
with said first focal plane of said second plurality of
lenses;

a second optical element having optical power
and having a fifth focal plane substantially coplanar with
30 said second focal plane of said first plurality of lenses;

52

wherein each wavelength channel of a WDM signal entering at port of said first array of optical ports is individually switchable to any of the port in first array of optical ports in a same row as the port where the WDM
5 signal entered and any of the second array of optical ports through appropriate control of the array of switching elements.

33. The wavelength cross connect according to
10 claim 32, wherein each of the first and second bulk optical element comprises a lens or a curved mirror.

34. The wavelength cross connect according to claim 32 or 33, wherein each of the first and second
15 plurality of dispersive elements comprise diffraction gratings, either reflection and transmission type or prisms.

35. An arrangement comprising:
a first plurality of lenses stacked
20 vertically;
a second plurality of lenses stacked vertically, spaced from said first plurality of lenses, non-overlapping in vertical space with said first plurality of lenses;
25 a first plurality of dispersive elements, with one dispersive element substantially in a first focal plane of each of said first plurality of lenses;
a second plurality of dispersive elements, with one dispersive element substantially in a second focal
30 plane of each of said second plurality of lenses;

53

a first array of switching elements controllable in two directions, the first array being substantially in a second focal plane of each of said first plurality of lenses;

5 a second array of switching elements controllable in two directions, the second array being substantially in a first focal plane of each of said second plurality of lenses;

10 a first plurality of two dimensional arrays of optical ports; a second plurality of two dimensional arrays of optical ports;

for each two dimensional array of said first plurality of two dimensional arrays of optical ports, a respective first bulk optical element having optical power and having a fourth focal plane substantially coplanar with said first focal plane of said second plurality of lenses;

for each two dimensional array of said second plurality of two dimensional arrays of optical ports, a respective second bulk optical element having optical power and having a fifth focal plane substantially coplanar with said second focal plane of said first plurality of lenses;

25 wherein each wavelength channel of a WDM signal entering at one of said first plurality of arrays of optical ports is individually switchable to any of the first plurality of arrays of optical ports and any of the second plurality of arrays of optical ports through appropriate control of the array of switching elements.

36. The arrangement according to claim 35, wherein
30 the first and second arrays of switching elements comprise MEMS switching elements.

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37. The arrangement according to claim 35 or 36, wherein the first and second arrays of the switching elements are transmissive.

5 38. The arrangement according to claim 35, 36 or 37, wherein each of the first bulk optical elements is selected from a group consisting of a lens, a curved mirror, an assembly of lenses and mirrors, and an assembly of lenses, mirrors and a curved mirror.

10

39. The arrangement according to any one of claims 35 to 38, wherein each of the second bulk optical elements is selected from a group consisting of a lens, a curved mirror, an assembly of lenses and mirrors, and an assembly
15 of lenses, mirrors and a curved mirror.

40. The arrangement according to any one of claims 35 to 39, wherein each of the first and second plurality of dispersive elements comprises diffraction gratings, either
20 reflection and transmission type, or prisms.

41. A wavelength selective switch comprising:

a two dimensional array of N optical ports;

a first bulk optical element having optical
25 power and having a first focal plane and a second focal plane;

a second bulk optical element having optical
power

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and having third focal plane and a fourth plane, the third focal plane being substantially coplanar with said second focal plane;

5 a dispersive element substantially in the fourth focal plane;

an array of switching elements substantially in the third focal plane, each switching element being adapted to switch in both a horizontal and vertical direction;

10 wherein each wavelength of a WDM signal entering at one of said array of N optical ports is individually switchable to any of the N optical ports through appropriate control of the array of switching elements.

42. A wavelength selective switch according to
15 claim 41 wherein the switching elements are MEMS switching elements.

43. A wavelength selective switch according to claim 41 wherein the switching elements are transmissive.

44. A wavelength selective switch according to
20 claim 41 wherein the first bulk optical element is selected from a group consisting of a lens, a curved mirror, an assembly of lenses and mirrors, and an assembly of lenses, mirrors and a curved mirror.

25 45. A wavelength selective switch according to claim 41 wherein the second bulk optical element is selected from a group consisting of a lens, a curved mirror, an

assembly of lenses and mirrors, and an assembly of lenses, mirrors and a curved mirror.

46. A wavelength selective switch according to claim 41 wherein the dispersive element is selected from a group comprising: a diffraction grating, either reflection and transmission type, prisms.

47. An optical wavelength switch comprising:

a telescope arrangement comprising a coupling lens and a main lens, the main lens having a first focal plane substantially coinciding with a focal plane of the coupling lens;

a two dimensional array of optical ports optically coupled to the coupling lens, the two dimensional array of optical ports having a first port and a plurality of second ports;

a dispersive element disposed substantially in a second focal plane of the main lens; and

an array of switching elements disposed substantially in the first focal plane, each switching element being adapted to switch light in both a horizontal and vertical direction;

the ports, the telescope arrangement, the dispersive elements, and the switching elements being arranged such that:

a) a multi-wavelength signal entering at the first port propagates through the telescope arrangement to the dispersive element where the multi-wavelength signal is demultiplexed into a plurality of wavelength channels;

5 b) each wavelength channel after demultiplexing propagates through the main lens to a respective switching element of the plurality of switching elements;

 c) each switching element is individually
10 controllable to reflect the wavelength channel to a selected one of the second ports via a path comprising in sequence the main lens, the dispersive element, the main lens, and the coupling lens.

48. The optical wavelength switch of claim 47
15 wherein the two dimensional array of optical ports, the coupling lens, the main lens, and the dispersive element are all disposed in a substantially co-axial manner.

49. The optical wavelength switch of claim 47
 wherein the dispersive element is a reflective diffraction
20 grating.

50. The optical wavelength switch of claim 47
 wherein the array of switching elements is an array of MEMS switching elements.

51. The optical wavelength switch of claim 47
25 wherein the two dimensional array of ports is arranged in a square, and the first port is in the middle of the square.

52. The optical wavelength switch of claim 47 wherein the switch is further adapted to allow any wavelength 25 channel to be switched back to the first port, the switch further comprising:

5 a circulator external to the first port that allows the multi-wavelength signal to enter the first port, and also allows optical wavelength channels to be switched to the first port without interfering with the multi-wavelength signal.

10 53. A method of optical wavelength switching, the method comprising in sequence:

directing a multi-wavelength signal through first port of a two dimensional array of optical ports and a telescope arrangement having a coupling lens and a main
15 lens;

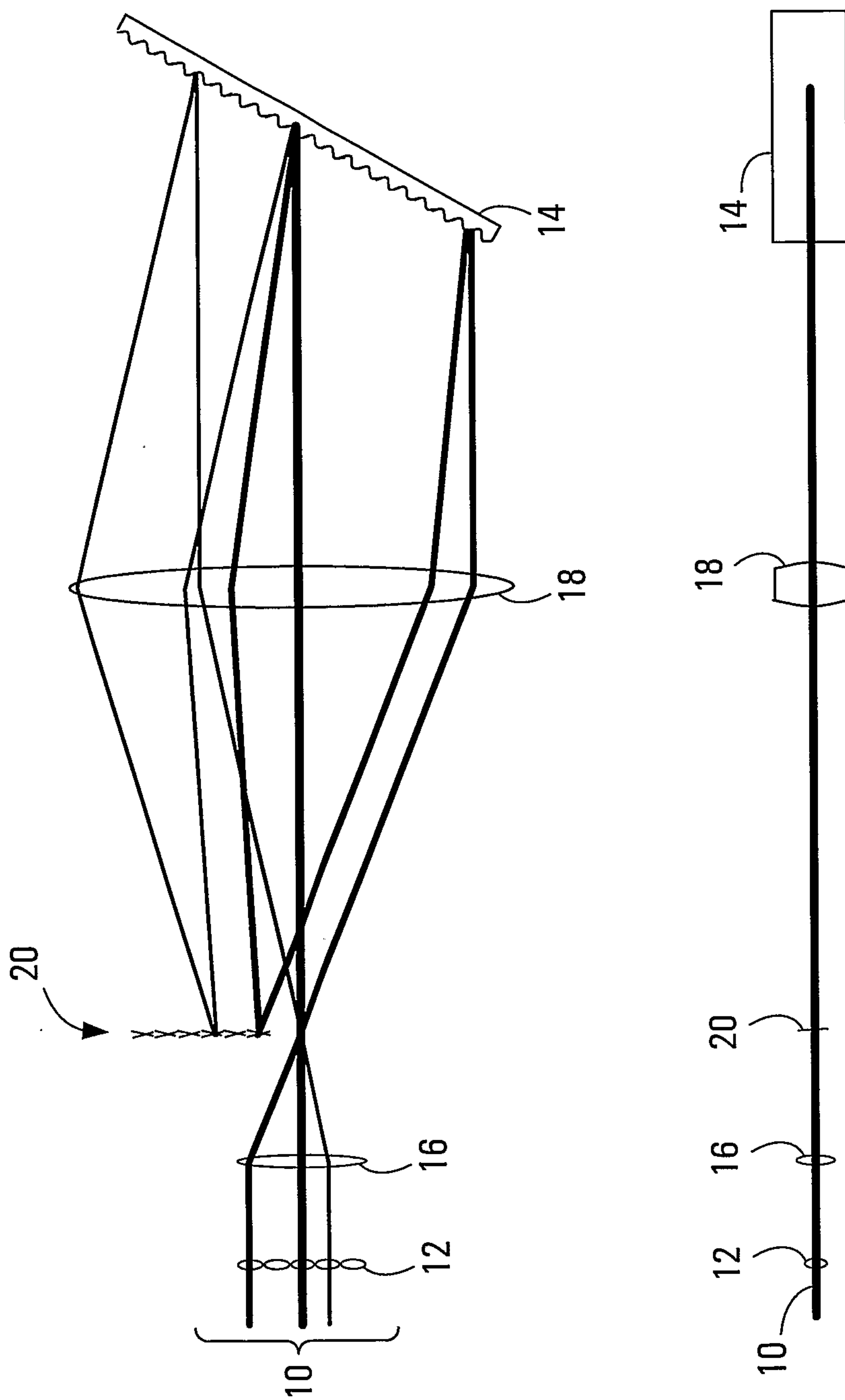
demultiplexing the multi-wavelength signal into a 10 plurality of wavelength channels using a dispersive element, each wavelength channel propagating through the main lens to a respective switching element;

20 controlling each switching element in vertical and horizontal directions to reflect each wavelength channel in 15 a respective selected direction, each wavelength channel propagating to one of the ports associated with the selected direction via the main lens, the dispersive
25 element, the main lens and the coupling lens.

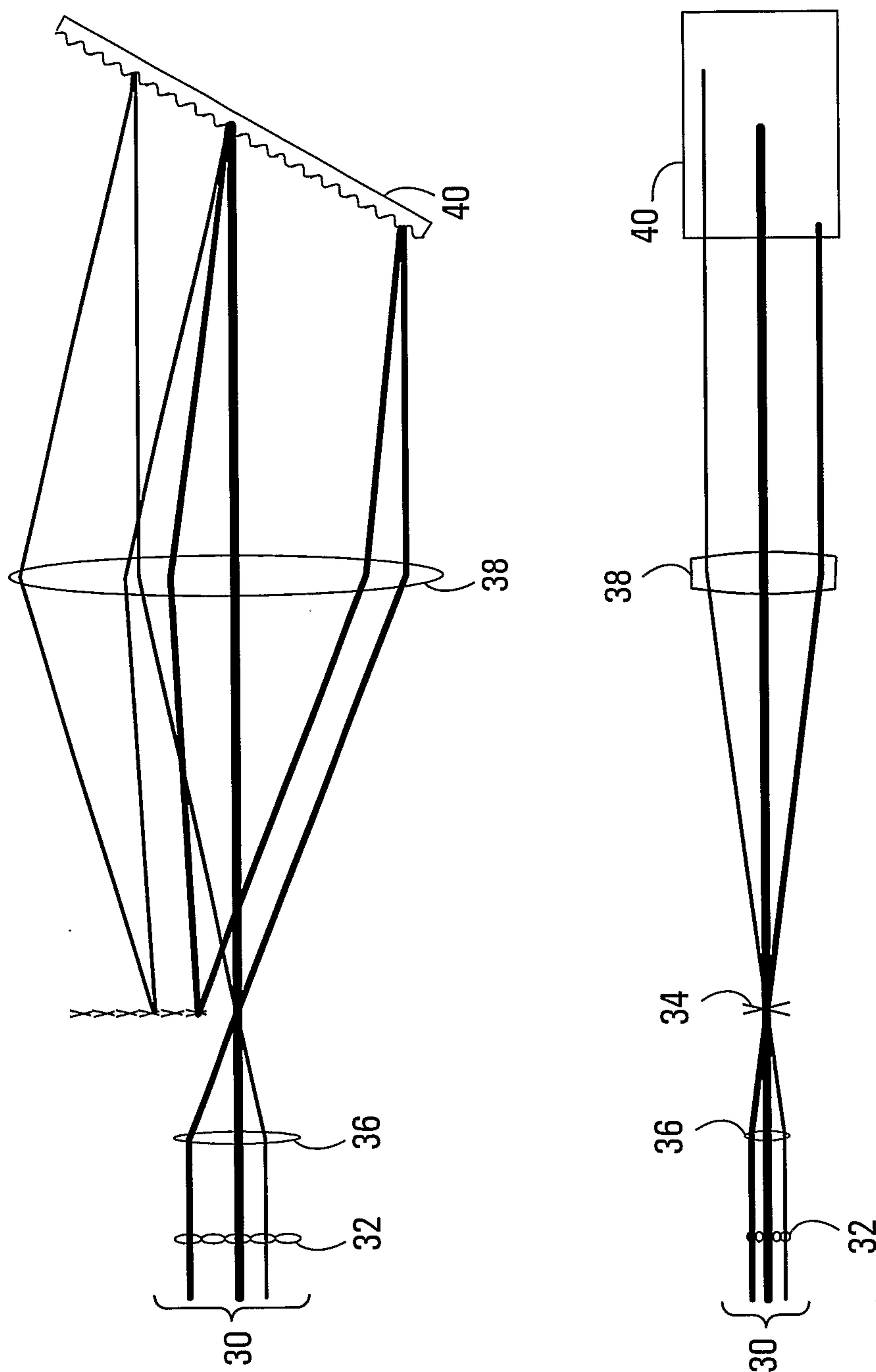
54 . The method of claim 53 wherein demultiplexing comprises using a reflective diffraction grating.

55. The method of claim 53 wherein controlling
5 each switching element comprises controlling a respective MEMS switching element.

1/13

**FIG. 1**
(PRIOR ART)

2/13



3/13

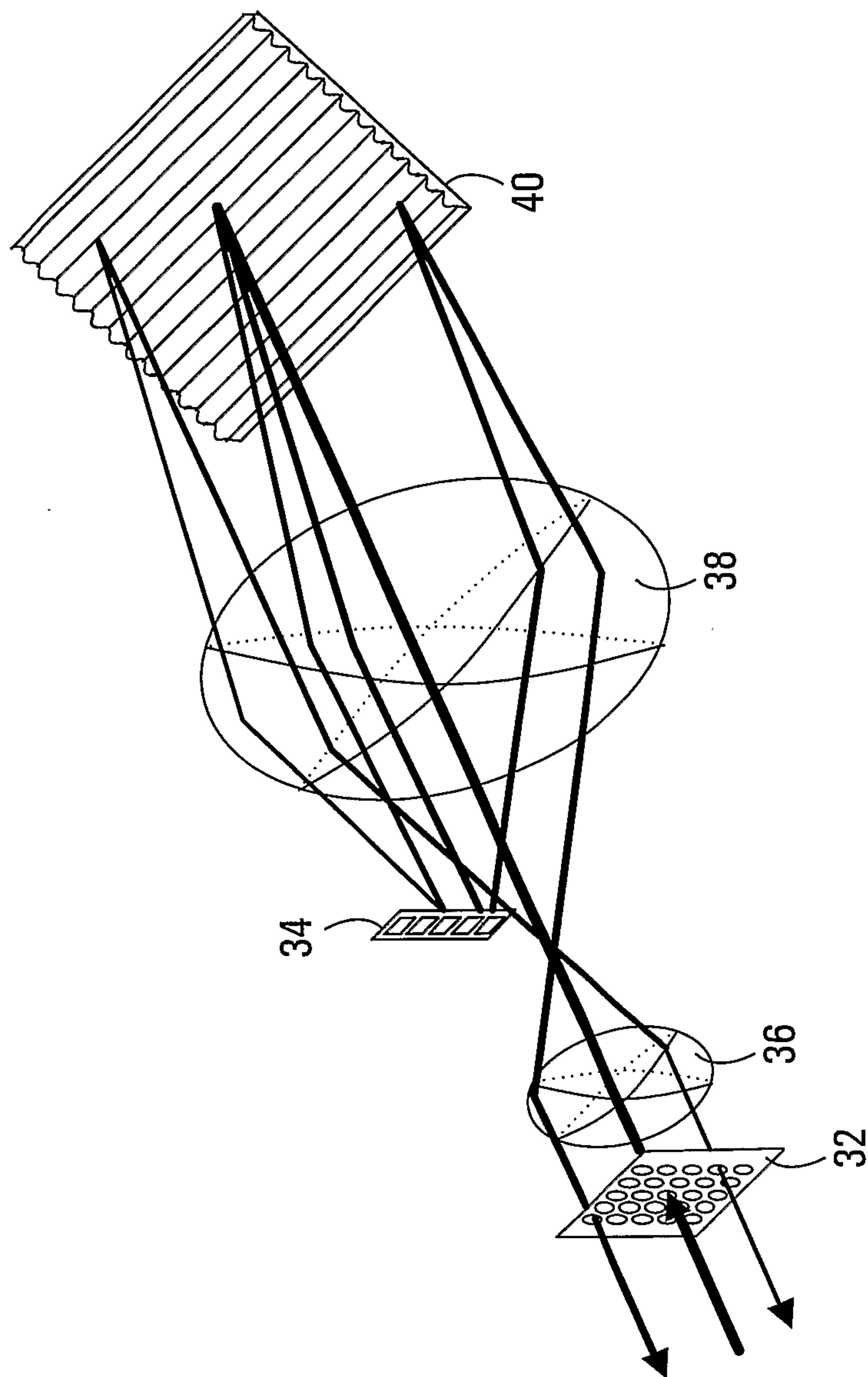


FIG. 3

FIG. 4A

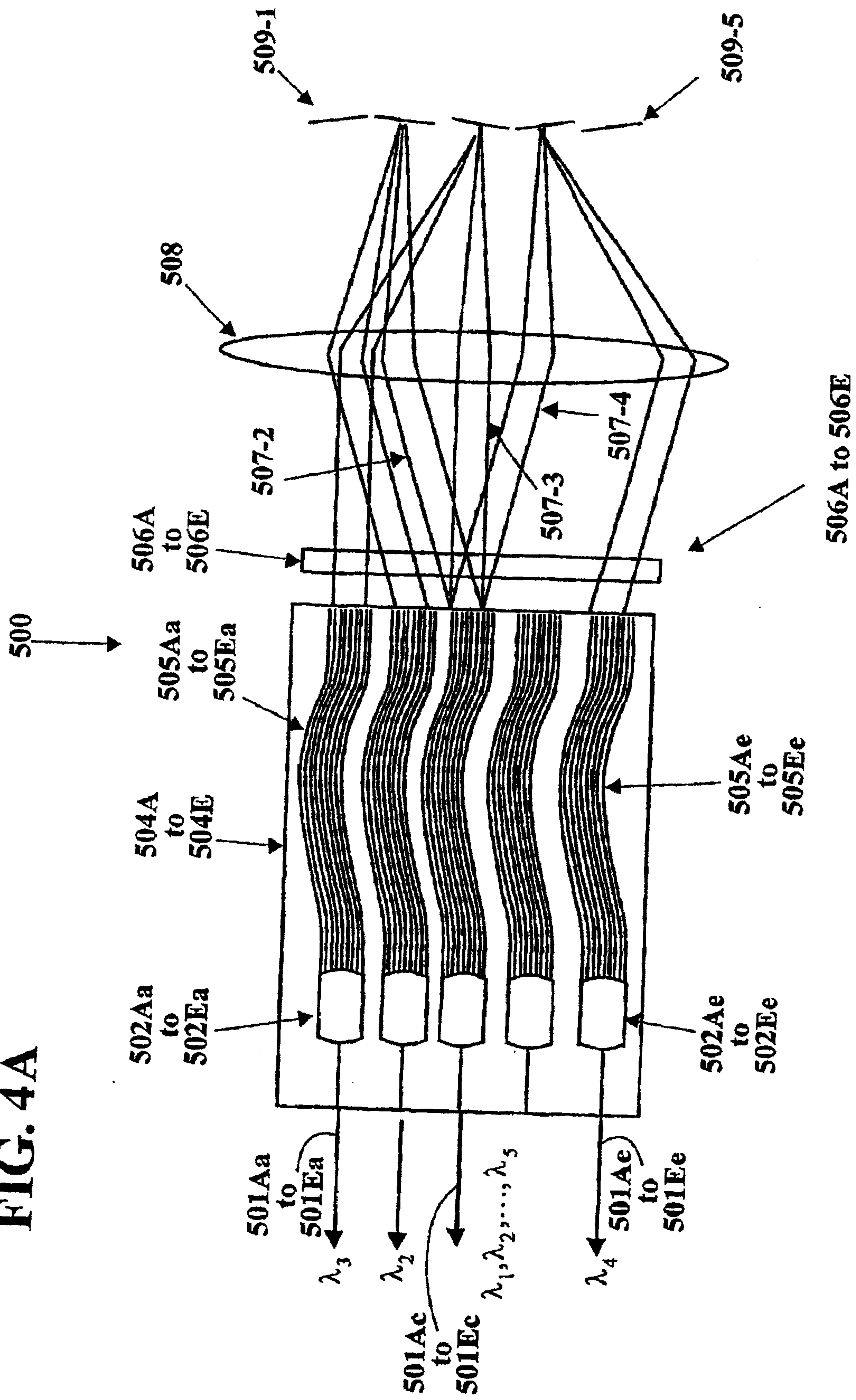
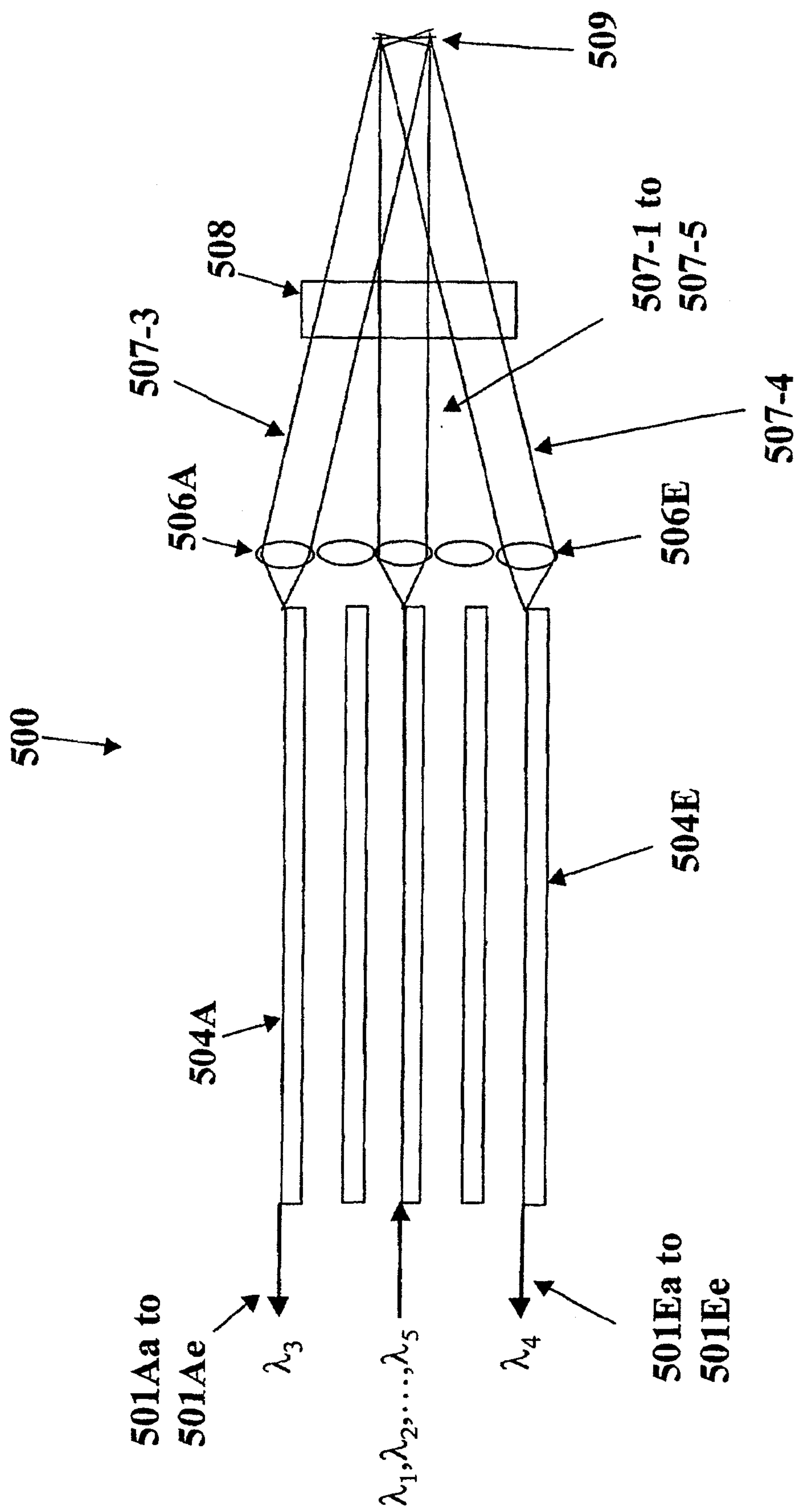


FIG. 4B



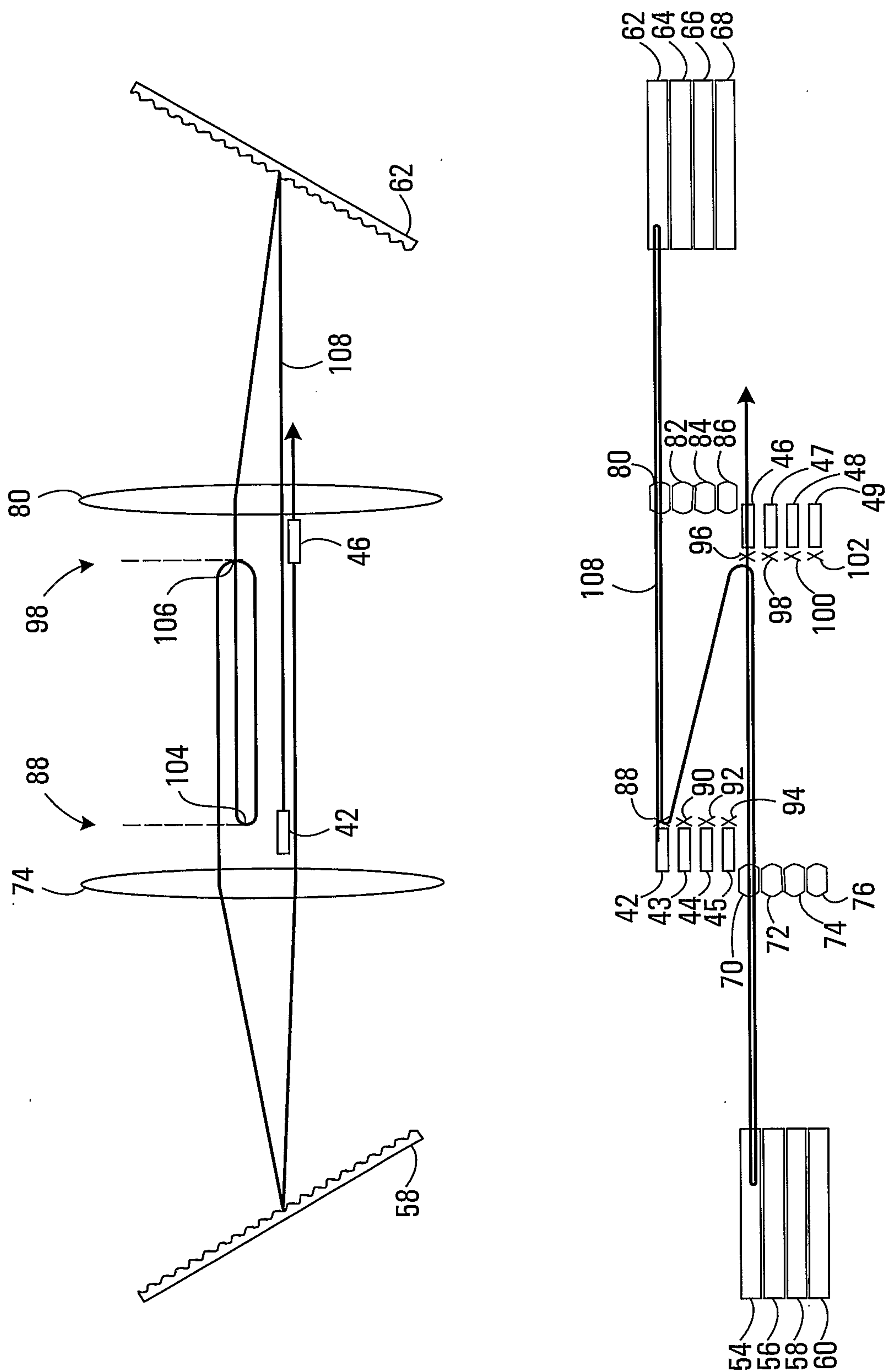


FIG. 5

6/13

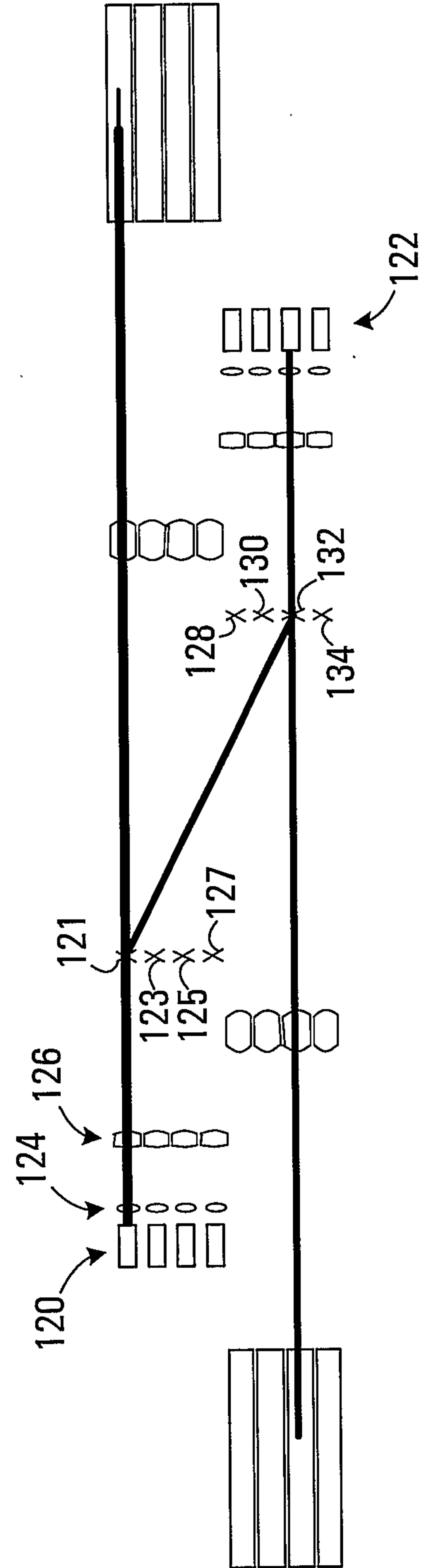
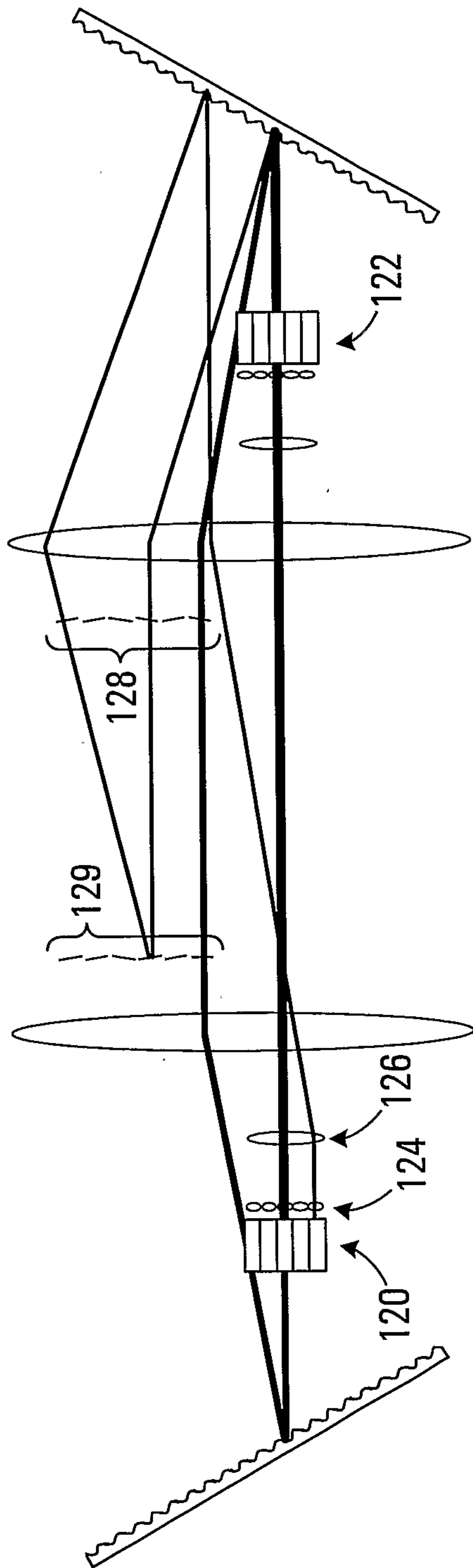
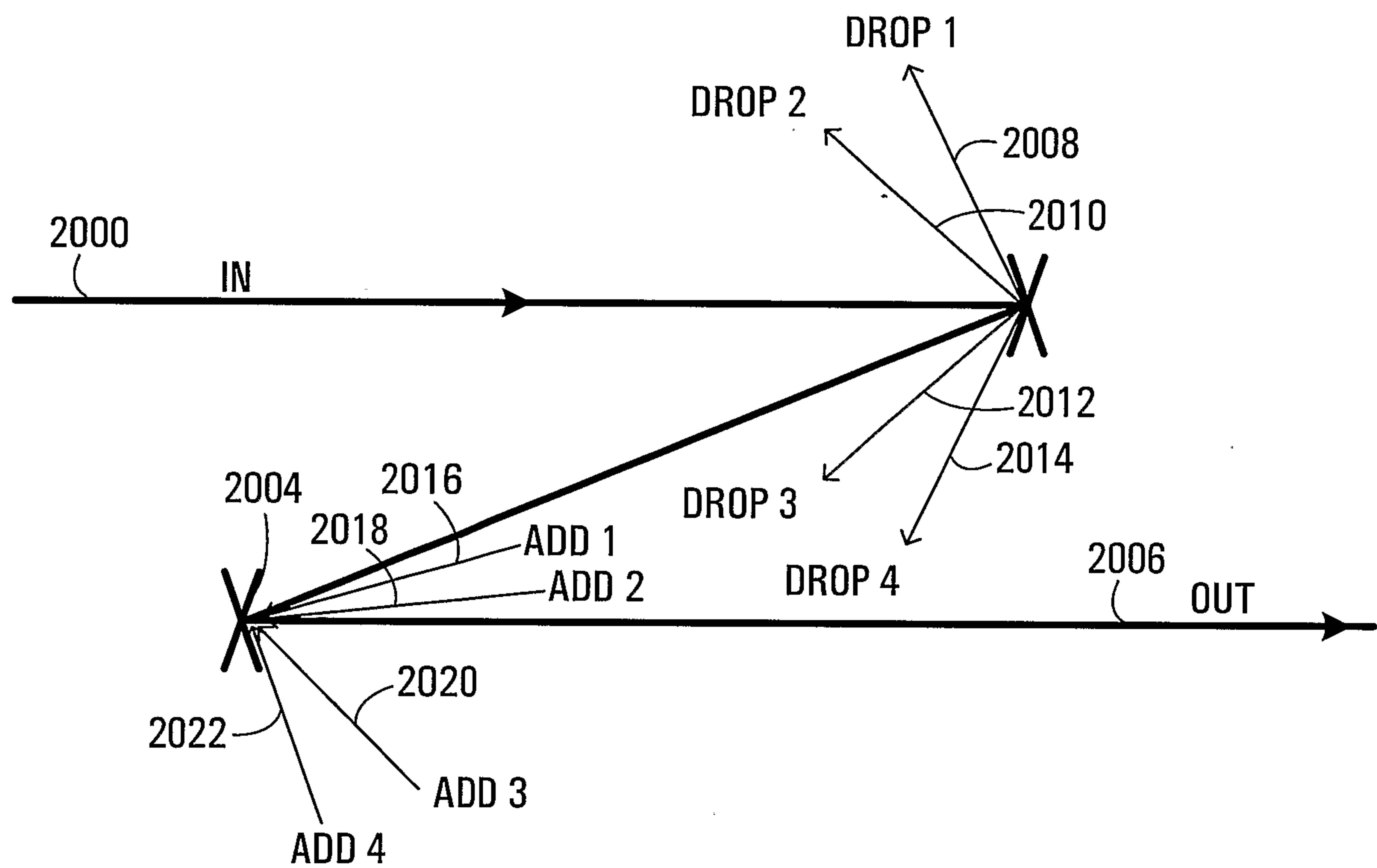


FIG. 6A

7/13

**FIG. 6B**

8/13

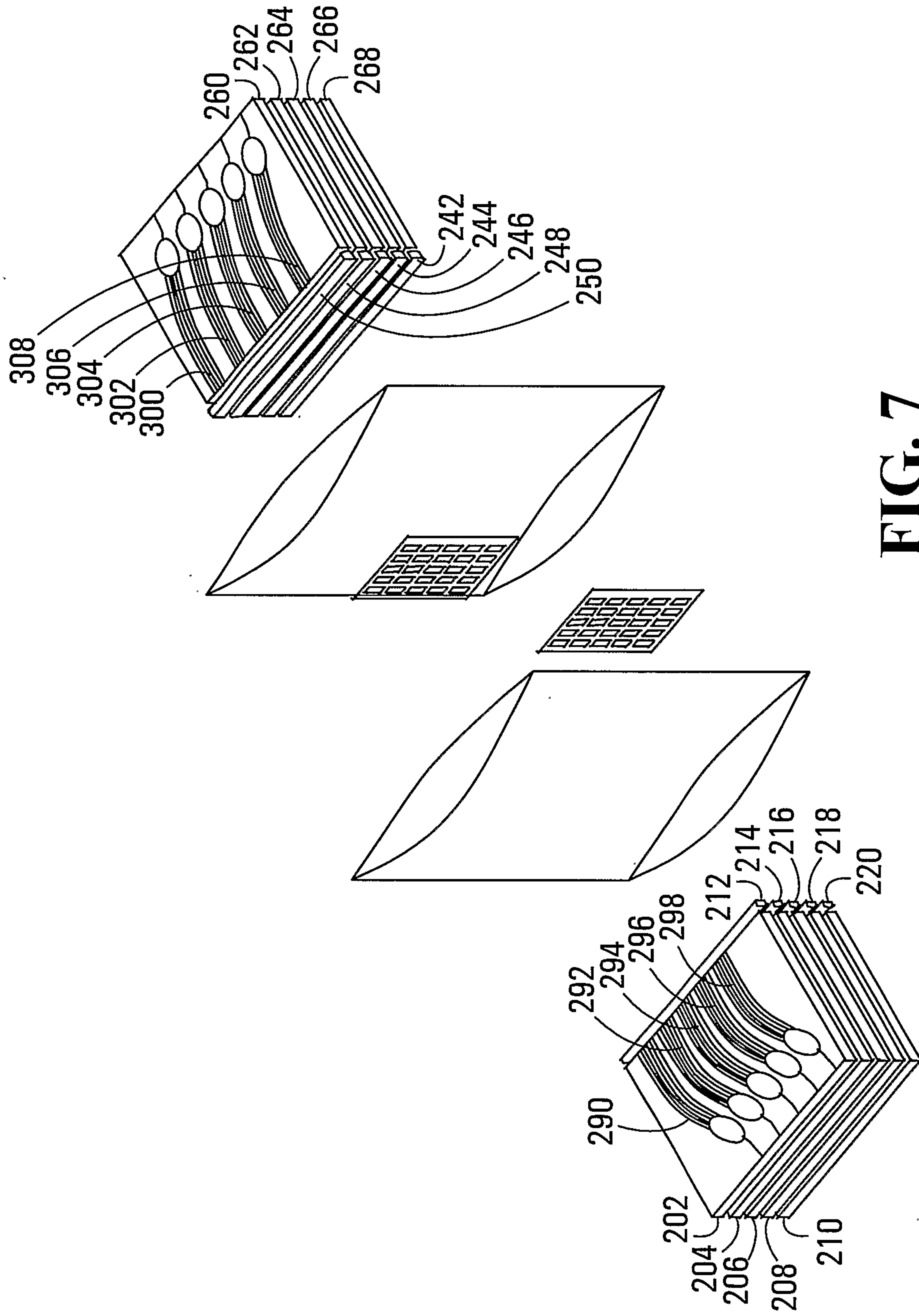


FIG. 7

9/13

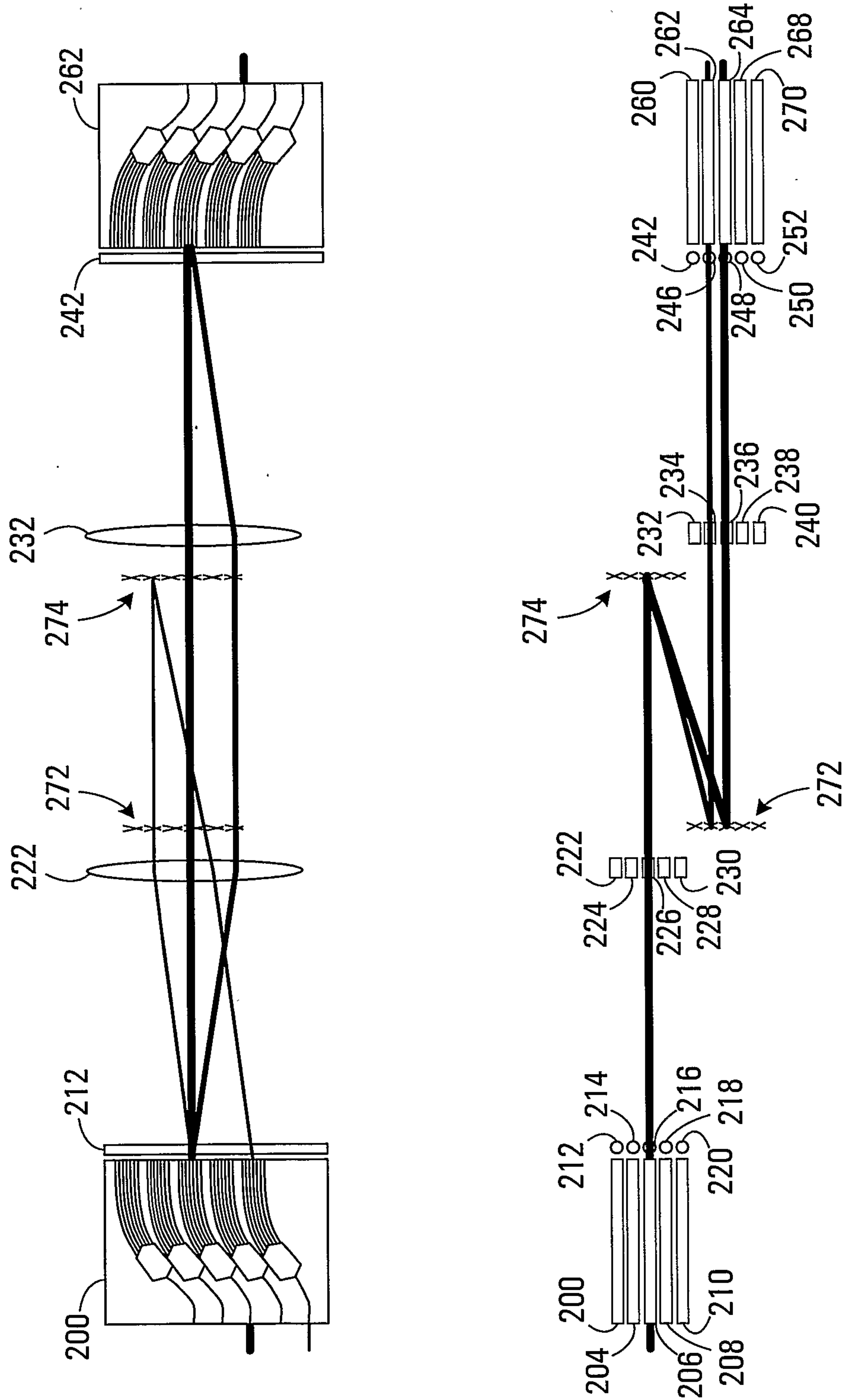


FIG. 8

10/13

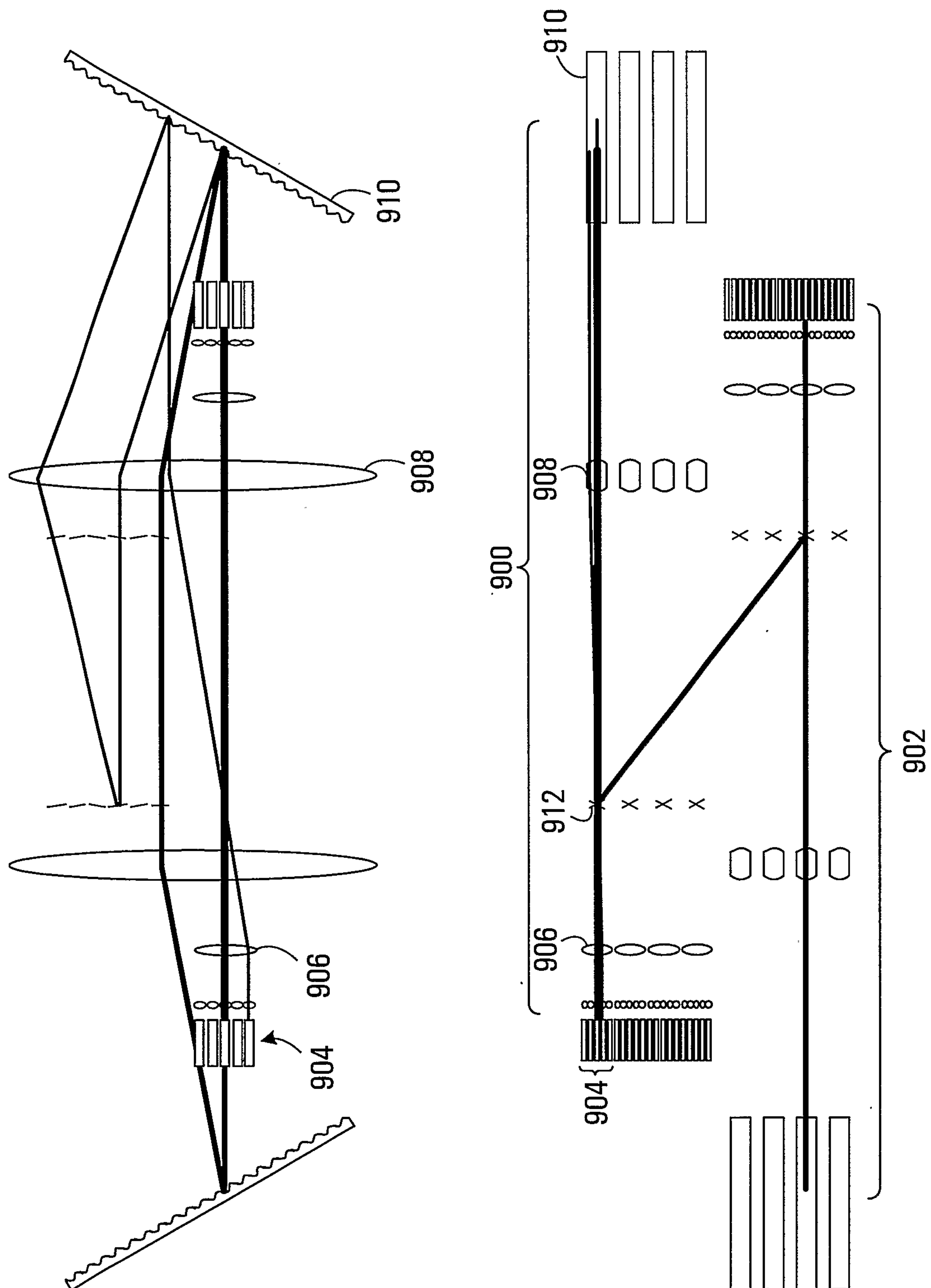


FIG. 9

11/13

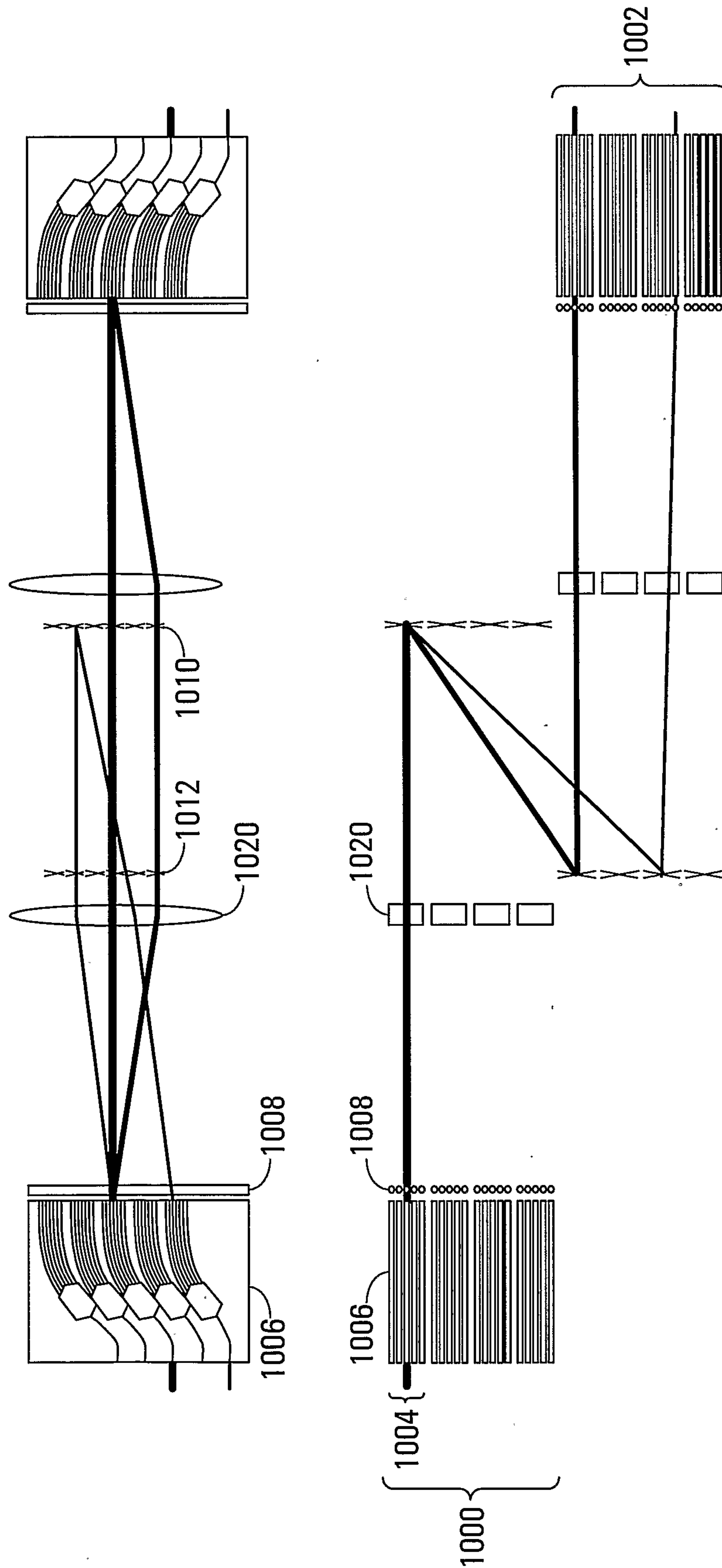


FIG. 10

12/13

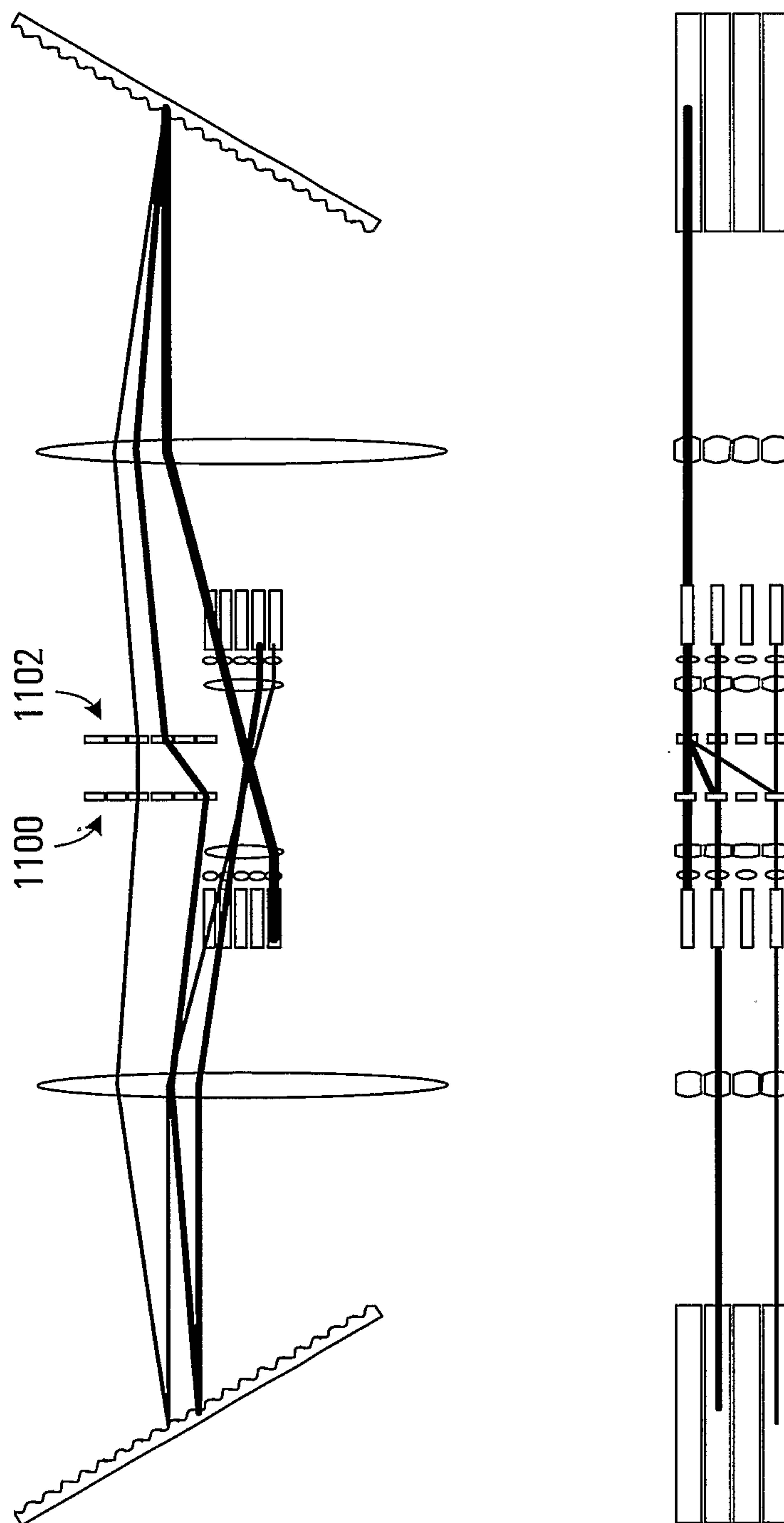


FIG. 11

13/13

