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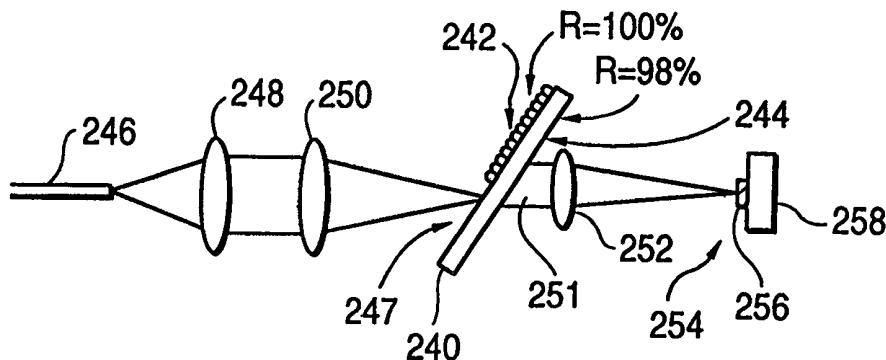
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(54) Title: OPTICAL APPARATUS WHICH USES A VIRTUALLY IMAGED PHASED ARRAY TO PRODUCE CHROMATIC DISPERSION

## (57) Abstract

An apparatus which adds "opposite dispersion" to light, to compensate for chromatic dispersion of the light caused by travelling through an optical fiber (246). The apparatus includes a virtually imaged phased array (VIPA) (240), and a light returning device (254). The VIPA provides angular dispersion to the light, and the light returning device returns the light back to the VIPA to undergo multiple reflections

inside the VIPA. The light returning device is typically a mirror. In this case, the mirror can be shaped so that the apparatus adds a constant dispersion to the light. Moreover, a lens (252) can be positioned so that (a) the light travels from the VIPA to the lens and the being focused by the lens to the light returning device, (b) the light returns from the light returning device to the lens and then, being directed by the lens, is parallel with the returned light travelling from the lens to the VIPA.



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TITLE OF THE INVENTION

OPTICAL APPARATUS WHICH USES A VIRTUALLY IMAGED PHASED  
ARRAY TO PRODUCE CHROMATIC DISPERSION

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part (CIP) of U.S.  
application number 08/796,842, filed February 7, 1997, and which  
is incorporated herein by reference.

10 This application is also a continuation-in-part (CIP) of  
U.S. application number 08/685,362, filed July 24, 1996, and  
which is incorporated herein by reference.

This application claims priority to Japanese patent  
application number 07-190535, filed July 26, 1995, in Japan, and  
15 which is incorporated herein by reference.

BACKGROUND OF THE INVENTION1. Field of the Invention

20 The present invention relates to an apparatus producing  
chromatic dispersion, and which can be used to compensate for  
chromatic dispersion accumulated in an optical fiber transmission  
line. More specifically, the present invention relates to an  
apparatus which uses a virtually imaged phased array to produce  
chromatic dispersion.

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## 2. Description of the Related Art

FIG. 1(A) is a diagram illustrating a conventional fiber optic communication system, for transmitting information via light. Referring now to FIG. 1(A), a transmitter 30 transmits pulses 32 through an optical fiber 34 to a receiver 36. Unfortunately, chromatic dispersion, also referred to as "wavelength dispersion", of optical fiber 34 degrades the signal quality of the system. More specifically, as a result of chromatic dispersion, the propagating speed of a signal in an optical fiber depends on the wavelength of the signal. For example, when a pulse with a longer wavelength (for example, a pulse with wavelengths representing a "red" color pulse) travels faster than a pulse with a shorter wavelength (for example, a pulse with wavelengths representing a "blue" color pulse), the dispersion is typically referred to as "normal" dispersion. By contrast, when a pulse with a shorter wavelength (such as a blue color pulse) is faster than a pulse with a longer wavelength (such as a red color pulse), the dispersion is typically referred to as "anomalous" dispersion.

Therefore, if pulse 32 consists of red and blue color pulses when emitted from transmitter 30, pulse 32 will be split as it travels through optical fiber 34 so that a separate red color pulse 38 and a blue color pulse 40 are received by receiver 36 at different times. FIG. 1(A) illustrates a case of "normal" dispersion, where a red color pulse travels faster than a blue color pulse.

As another example of pulse transmission, FIG. 1(B) is a diagram illustrating a pulse 42 having wavelength components continuously from blue to red, and transmitted by transmitter 30. FIG. 1(C) is a diagram illustrating pulse 42 when arrived at receiver 36. Since the red component and the blue component travel at different speeds, pulse 42 is broadened in optical fiber 34 and, as illustrated by FIG. 1(C), is distorted by chromatic dispersion. Such chromatic dispersion is very common in fiber optic communication systems, since all pulses include a finite range of wavelengths.

Therefore, for a fiber optic communication system to provide a high transmission capacity, the fiber optic communication system must compensate for chromatic dispersion.

FIG. 2 is a diagram illustrating a fiber optic communication system having an opposite dispersion component to compensate for chromatic dispersion. Referring now to FIG. 2, generally, an opposite dispersion component 44 adds an "opposite" dispersion to a pulse to cancel dispersion caused by travelling through optical fiber 34.

There are conventional devices which can be used as opposite dispersion component 44. For example, FIG. 3 is a diagram illustrating a fiber optic communication system having a dispersion compensation fiber which has a special cross-section index profile and thereby acts as an opposite dispersion component, to compensate for chromatic dispersion. Referring now to FIG. 3, a dispersion compensation fiber 46 provides an opposite dispersion to cancel dispersion caused by optical fiber 34. However, a dispersion compensation fiber is expensive to

manufacture, and must be relatively long to sufficiently compensate for chromatic dispersion. For example, if optical fiber 34 is 100 km in length, then dispersion compensation fiber 46 should be approximately 20 to 30 km in length.

5           FIG. 4 is a diagram illustrating a chirped grating for use as an opposite dispersion component, to compensate for chromatic dispersion. Referring now to FIG. 4, light travelling through an optical fiber and experiencing chromatic dispersion is provided to an input port 48 of an optical circulator 50.  
10   Circulator 50 provides the light to chirped grating 52. Chirped grating 52 reflects the light back towards circulator 50, with different wavelength components reflected at different distances along chirped grating 52 so that different wavelength components travel different distances to thereby compensate for chromatic  
15   dispersion. For example, chirped grating 52 can be designed so that longer wavelength components are reflected at a farther distance along chirped grating 52, and thereby travel a farther distance than shorter wavelength components. Circulator 50 then provides the light reflected from chirped grating 52 to an output  
20   port 54. Therefore, chirped grating 52 can add opposite dispersion to a pulse.

Unfortunately, a chirped grating has a very narrow bandwidth for reflecting pulses, and therefore cannot provide a wavelength band sufficient to compensate for light including many  
25   wavelengths, such as a wavelength division multiplexed light. A number of chirped gratings may be cascaded for wavelength multiplexed signals, but this results in an expensive system. Instead, a chirped grating with a circulator, as in FIG. 4, is

more suitable for use when a single channel is transmitted through a fiber optic communication system.

FIG. 5 is a diagram illustrating a conventional diffraction grating, which can be used in producing chromatic dispersion.

5 Referring now to FIG. 5, a diffraction grating 56 has a grating surface 58. Parallel lights 60 having different wavelengths are incident on grating surface 58. Lights are reflected at each step of grating surface 58 and interfere with each other. As a result, lights 62, 64 and 66 having different wavelengths are  
10 output from diffraction grating 56 at different angles. A diffraction grating can be used in a spatial grating pair arrangement, as discussed in more detail below, to compensate for chromatic dispersion.

More specifically, FIG. 6(A) is a diagram illustrating a  
15 spatial grating pair arrangement for use as an opposite dispersion component, to compensate for chromatic dispersion. Referring now to FIG. 6(A), light 67 is diffracted from a first diffraction grating 68 into a light 69 for shorter wavelength and a light 70 for longer wavelength. These lights 69 and 70 are  
20 then diffracted by a second diffraction grating 71 into lights propagating in the same direction. As can be seen from FIG. 6(A), wavelength components having different wavelengths travel different distances, to add opposite dispersion and thereby compensate for chromatic dispersion. Since longer wavelengths  
25 (such as lights 70) travel longer distance than shorter wavelengths (such as lights 69), a spatial grating pair arrangement as illustrated in FIG. 6(A) has anomalous dispersion.

FIG. 6(B) is a diagram illustrating an additional spatial grating pair arrangement for use as an opposite dispersion component, to compensate for chromatic dispersion. As illustrated in FIG. 6(B), lenses 72 and 74 are positioned between first and second diffraction gratings 68 and 71 so that they share one of the focal points. Since longer wavelengths (such as lights 70) travel shorter distance than shorter wavelengths (such as lights 69), a spatial grating pair arrangement as illustrated in FIG. 6(B) has normal dispersion.

A spatial grating pair arrangement as illustrated in FIGS. 6(A) and 6(B) is typically used to control dispersion in a laser resonator. However, a practical spatial grating pair arrangement cannot provide a large enough dispersion to compensate for the relatively large amount of chromatic dispersion occurring in a fiber optic communication system. More specifically, the angular dispersion produced by a diffraction grating is usually extremely small, and is typically approximately 0.05 degrees/nm. Therefore, to compensate for chromatic dispersion occurring in a fiber optic communication system, first and second gratings 68 and 71 would have to be separated by very large distances, thereby making such a spatial grating pair arrangement impractical.

#### SUMMARY OF THE INVENTION

Therefore, it is an object of the present invention to provide an apparatus which produces chromatic dispersion, and which is practical for compensating for chromatic dispersion accumulated in an optical fiber.



Objects of the present invention are achieved by providing an apparatus which includes a device herein referred to as a "virtually imaged phased array", or "VIPA". The VIPA produces a light propagating away from the VIPA. The apparatus also includes a light returning device which returns the light back to the VIPA to undergo multiple reflection inside the VIPA.

Objects of the present invention are also achieved by providing an apparatus which includes a VIPA that receives an input light having a wavelength within a continuous range of wavelengths and produces a continuously corresponding output light. The output light is spatially distinguishable (for example, it travels in a different direction) from an output light formed for an input light having any other wavelength within the continuous range of wavelengths. If the output light is distinguishable by its travelling angle, the apparatus has an angular dispersion.

Further, objects of the present invention are achieved by providing a VIPA and a light returning device, wherein the VIPA includes a passage area and a transparent material. The passage area allows light to be received into, and be output from, the VIPA. The transparent material has first and second surfaces thereon, the second surface having a reflectivity which allows a portion of light incident thereon to be transmitted therethrough. An input light is received in the VIPA through the passage area and is reflected a plurality of times in the transparent material between the first and second surfaces to cause a plurality of lights to be transmitted through the second surface. The plurality of transmitted lights interfere with each

other to produce an output light. The input light is at a wavelength within a continuous range of wavelengths and the output light is spatially distinguishable from an output light formed for an input light having any other wavelength within the continuous range of wavelengths. The light returning device causes the output light to be returned in the exactly opposite direction back to the second surface and pass therethrough into the VIPA so that the output light undergoes multiple reflection in the VIPA and is then output from the passage area of the VIPA to the input path.

In addition, object of the present invention are achieved by providing an apparatus which includes a VIPA that produces a plurality of output lights at the same wavelength of the input light and having different interference orders. The apparatus also includes a light returning device which returns the output light in one of the interference orders to the VIPA, and does not return the other output lights. In this manner, only light corresponding to a single interference order is returned back to the VIPA.

Objects of the present invention are further achieved by providing an apparatus which includes a VIPA, a light returning device and a lens. The VIPA receives an input light and produces a corresponding output light propagating away from the VIPA. The light returning device receives the output light from the VIPA and then returns the output light back to the VIPA. The lens is positioned so that (a) the output light travels from the VIPA to the light returning device by travelling from the VIPA to the lens and then being focused by the lens to the light returning

device, (b) the output light returns from the light returning device to the VIPA by travelling from the light returning device to the lens and then being directed by the lens to the VIPA, and (c) the output light travelling from the VIPA to the lens is parallel with, and in the opposite direction to, the returned output light travelling from the lens to the VIPA. Moreover, the output light travelling from the VIPA to the lens does not overlap with the returned output light travelling from the lens to the VIPA.

Moreover, objects of the present invention are achieved by providing an apparatus which includes a VIPA, a mirror and a lens. The VIPA receives an input light and produces a corresponding output light propagating away from the VIPA. The lens focuses the output light onto the mirror so that the mirror reflects the output light and the reflected light is directed by the lens back to the VIPA. The mirror is shaped so that the apparatus provides a constant chromatic dispersion.

#### BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and advantages of the invention will become apparent and more readily appreciated from the following description of the preferred embodiments, taken in conjunction with the accompanying drawings of which:

FIG. 1(A) (prior art) is a diagram illustrating a conventional fiber optic communication system.

FIG. 1(B) is a diagram illustrating a pulse before transmission through a fiber in a conventional fiber optic communication system.

FIG. 1(C) is a diagram illustrating a pulse after being transmitted through a fiber in a conventional fiber optic communication system.

FIG. 2 (prior art) is a diagram illustrating a fiber optic communication system having an opposite dispersion component to compensate for chromatic dispersion.

FIG. 3 (prior art) is a diagram illustrating a fiber optic communication system having a dispersion compensation fiber as an opposite dispersion component.

FIG. 4 (prior art) is a diagram illustrating a chirped grating for use as an opposite dispersion component, to compensate for chromatic dispersion.

FIG. 5 (prior art) is a diagram illustrating a conventional diffraction grating.

FIG. 6(A) (prior art) is a diagram illustrating a spatial grating pair arrangement for production of anomalous dispersion.

FIG. 6(B) (prior art) is a diagram illustrating a spatial grating pair arrangement for production of normal dispersion.

FIG. 7 is a diagram illustrating a VIPA, according to an embodiment of the present invention.

FIG. 8 is a detailed diagram illustrating the VIPA of FIG. 7, according to an embodiment of the present invention.

FIG. 9 is a diagram illustrating a cross-section along lines IX--IX of the VIPA illustrated in FIG. 7, according to embodiment of the present invention.

FIG. 10 is a diagram illustrating interference between reflections produced by a VIPA, according to an embodiment of the present invention.

FIG. 11 is a diagram illustrating a cross-section along lines IX-IX of the VIPA illustrated in FIG. 7, for determining the tilt angle of input light, according to an embodiment of the present invention.

5        FIGS. 12(A), 12(B), 12(C) and 12(D) are diagrams illustrating a method for producing a VIPA, according to an embodiment of the present invention.

FIG. 13 is a diagram illustrating an apparatus which uses a VIPA as an angular dispersion component to produce chromatic  
10 dispersion, according to an embodiment of the present invention.

FIG. 14 is a more detailed diagram illustrating the operation of the apparatus in FIG. 13, according to an embodiment of the present invention.

FIG. 15 is a diagram illustrating various orders of interference of a VIPA, according to an embodiment of the present  
15 invention.

FIG. 16 is a graph illustrating the chromatic dispersion for several channels of a wavelength division multiplexed light, according to an embodiment of the present invention.

20        FIG. 17 is a diagram illustrating different channels of a wavelength division multiplexed light being focused at different points on a mirror by a VIPA, according to an embodiment of the present invention.

FIG. 18 is a diagram illustrating a side view of an apparatus which uses a VIPA to provide variable chromatic  
25 dispersion to light, according to an embodiment of the present invention.

FIG. 19 is a diagram illustrating a side view of an apparatus which uses a VIPA to provide variable chromatic dispersion to light, according to an additional embodiment of the present invention.

5        FIGS. 20(A) and 20(B) are diagrams illustrating side views of an apparatus which uses a VIPA to provide chromatic dispersion to light, according to additional embodiments of the present invention.

10       FIG. 21 is a graph illustrating the output angle of a luminous flux from a VIPA versus wavelength of the luminous flux, according to an embodiment of the present invention.

FIG. 22 is a graph illustrating the angular dispersion of a VIPA versus the wavelength of a luminous flux, according to an embodiment of the present invention.

15       FIG. 23 is a graph illustrating the effect of different mirror types in an apparatus using a VIPA, according to embodiments of the present invention.

20       FIG. 24 is a diagram illustrating chromatic dispersion versus wavelength in an apparatus using a VIPA, for different types of mirrors used in the apparatus, according to embodiments of the present invention.

FIG. 25 is a graph illustrating the effect of a mirror in an apparatus which uses a VIPA, according to embodiments of the present invention.

25       FIG. 26 is a graph illustrating constant chromatic dispersion of an apparatus using a VIPA, according to embodiments of the present invention.

FIG. 27 is a graph illustrating characteristics of different mirror designs for an apparatus using a VIPA, according to embodiments of the present invention.

FIGS. 28(A), 28(B), 28(C), 28(D), 28(E) and 28(F) are diagrams illustrating examples of mirrors of an apparatus using a VIPA, according to embodiments of the present invention.

FIG. 29 is a diagram illustrating a side view of an apparatus which uses a VIPA to provide variable dispersion to light, according to a further embodiment of the present invention.

FIG. 30 is a diagram illustrating a top view of the apparatus in FIG. 13, combined with a circulator, according to an embodiment of the present invention.

FIG. 31 is a diagram illustrating a top view of an apparatus using a VIPA, according to an embodiment of the present invention.

FIG. 32 is a diagram illustrating a top view of an apparatus using a VIPA, according to an additional embodiment of the present invention.

FIG. 33 is a diagram illustrating a single collimating lens for an apparatus using a VIPA, according to an embodiment of the present invention.

FIG. 34 is a diagram illustrating a controller for controlling the temperature of a VIPA, according to an embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference will now be made in detail to the present preferred embodiments of the present invention, examples of which are illustrated in the accompanying drawings, wherein like  
5 reference numerals refer to like elements throughout.

FIG. 7 is a diagram illustrating a virtually imaged phased array (VIPA), according to an embodiment of the present invention. Moreover, hereinafter, the terms "virtually imaged phased array" and "VIPA" may be used interchangeably.

Referring now to FIG. 7, a VIPA 76 is preferably made of a  
10 thin plate of glass. An input light 77 is focused into a line 78 with a lens 80, such as a semi-cylindrical lens, so that input light 77 travels into VIPA 76. Line 78 is hereinafter referred to as "focal line 78". Input light 77 radially propagates from  
15 focal line 78 to be received inside VIPA 76. VIPA 78 then outputs a luminous flux 82 of collimated light, where the output angle of luminous flux 82 varies as the wavelength of input light 77 changes. For example, when input light 77 is at a wavelength  $\lambda_1$ , VIPA 76 outputs a luminous flux 82a at wavelength  $\lambda_1$  in a  
20 specific direction. When input light 77 is at a wavelength  $\lambda_2$ , VIPA 76 outputs a luminous flux 82b at wavelength  $\lambda_2$  in a different direction. Therefore, VIPA 76 produces luminous fluxes 82a and 82b which are spatially distinguishable from each other.

FIG. 8 is a detailed diagram illustrating VIPA 76, according  
25 to an embodiment of the present invention. Referring now to FIG. 8, VIPA 76 includes a plate 120 made of, for example, glass, and having reflecting films 122 and 124 thereon. Reflecting film 122 preferably has a reflectance of approximately 95% or higher, but



less than 100%. Reflecting film 124 preferably has a reflectance of approximately 100%. A radiation window 126 is formed on plate 120 and preferably has a reflectance of approximately 0% reflectance.

5           Input light 77 is focused into focal line 78 by lens 80 through radiation window 126, to undergo multiple reflection between reflecting films 122 and 124. Focal line 78 is preferably on the surface of plate 120 to which reflecting film 122 is applied. Thus, focal line 78 is essentially line focused  
10           onto reflecting film 122 through radiation window 126. The width of focal line 78 can be referred to as the "beam waist" of input light 77 as focused by lens 80. Thus, the embodiment of the present invention as illustrated is FIG. 8 focuses the beam waist of input light 77 onto the far surface (that is, the surface  
15           having reflecting film 122 thereon) of plate 120. By focusing the beam waist on the far surface of plate 120, the present embodiment of the present invention reduces the possibility of overlap between (i) the area of radiation window 126 on the surface of plate 120 covered by input light 77 as it travels  
20           through radiation window 126 (for example, the area "a" illustrated in FIG. 11, discussed in more detail further below), and (ii) the area on reflecting film 124 covered by input light 77 when input light 77 is reflected for the first time by reflecting film 124 (for example, the area "b" illustrated in  
25           FIG. 11, discussed in more detail further below). It is desirable to reduce such overlap to ensure proper operation of the VIPA.

In FIG. 8, an optical axis 132 of input light 77 has a small tilt angle  $\theta$ . Upon the first reflection off of reflecting film 122, 5% of the light passes through reflecting film 122 and diverges after the beam waist, and 95% of the light is reflected towards reflecting film 124. After being reflecting by reflecting film 124 for the first time, the light again hits reflecting film 122 but is displaced by an amount  $d$ . Then, 5% of the light passes through reflecting film 122. In a similar manner, as illustrated in FIG. 8, the light is split into many paths with a constant separation  $d$ . The beam shape in each path forms so that the light diverges from virtual images 134 of the beam waist. Virtual images 134 are located with constant spacing  $2t$  along a line that is normal to plate 120, where  $t$  is the thickness of plate 120. The positions of the beam waists in virtual images 134 are self-aligned, and there is no need to adjust individual positions. The lights diverging from virtual images 134 interfere with each other and form collimated light 136 which propagates in a direction that changes in accordance with the wavelength of input light 77.

The spacing of light paths is  $d = 2t\sin\theta$ , and the difference in the path lengths between adjacent beams is  $2t\cos\theta$ . The angular dispersion is proportional to the ratio of these two numbers, which is  $\cot\theta$ . As a result, a VIPA produces a significantly large angular dispersion.

As easily seen from FIG. 8, the term "virtually imaged phased array" arises from the formation of an array of virtual images 134.

FIG. 9 is a diagram illustrating a cross-section along lines IX--IX of VIPA 76 illustrated in FIG. 7, according to embodiment of the present invention. Referring now to FIG. 9, plate 120 has reflecting surfaces 122 and 124 thereon. Reflecting surfaces 122 and 124 are in parallel with each other and spaced by the thickness  $t$  of plate 120. Reflecting surfaces 122 and 124 are typically reflecting films deposited on plate 120. As previously described, reflecting surface 124 has a reflectance of approximately 100%, except in radiation window 126, and reflecting surface 122 has a reflectance of approximately 95% or higher. Therefore, reflecting surface 122 has a transmittance of approximately 5% or less so that approximately 5% or less of light incident on reflecting surface 122 will be transmitted therethrough and approximately 95% or more of the light will be reflected. The reflectances of reflecting surfaces 122 and 124 can easily be changed in accordance with the specific VIPA application. However, generally, reflecting surface 122 should have a reflectance which is less than 100% so that a portion of incident light can be transmitted therethrough.

Reflecting surface 124 has radiation window 126 thereon. Radiation window 126 allows light to pass therethrough, and preferably has no reflectance, or a very low reflectance. Radiation window 126 receives input light 77 to allow input light 77 to be received between, and reflected between, reflecting surfaces 122 and 124.

Since FIG. 9 represents a cross-section along lines IX--IX in FIG. 7, focal line 78 in FIG. 7 appears as a "point" in FIG. 9. Input light 77 then propagates radially from focal line 78. Moreover, as illustrated in FIG. 9, focal line 78 is positioned on reflecting surface 122. Although it is not required for focal line 78 to be on reflecting surface 122, a shift in the positioning of focal line 78 may cause small changes in the characteristics of VIPA 76.

As illustrated in FIG. 9, input light 77 enters plate 120 through an area A0 in radiation window 126, where points P0 indicate peripheral points of area A0.

Due to the reflectivity of reflecting surface 122, approximately 95% or more of input light 77 is reflected by reflecting surface 122 and is incident on area A1 of reflecting surface 124. Points P1 indicate peripheral points of area A1. After reflecting off area A1 on reflecting surface 124, input light 77 travels to reflecting surface 122 and is partially transmitted through reflecting surface 122 as output light Out1 defined by rays R1. In this manner, as illustrated in FIG. 9, input light 77 experiences multiple reflections between reflecting surfaces 122 and 124, wherein each reflection off of reflecting surface 122 also results in a respective output light being transmitted therethrough. Therefore, for example, each time immediately after input light 77 reflects off of areas A2, A3 and A4 on reflecting surface 124, input light 77 reflects off of reflecting surface 122 to produce output lights Out2, Out3 and Out4. Points P2 indicate peripheral points of area A2, points P3 indicate peripheral points of area A3, and points P4 indicate

peripheral points of area A4. Output light Out2 is defined by rays R2, output light Out3 is defined by rays R3 and output light Out4 is defined by rays R4. Although FIG. 9 only illustrates output lights Out0, Out1, Out2, Out3 and Out4, there will actually be many more output lights, depending on the power on input light 77 and the reflectances of reflecting surfaces 122 and 124. As will be discussed in more detail further below, the output lights interfere with each other to produce a luminous flux having a direction which changes in accordance with the wavelength of input light 77. Therefore, the luminous flux can be described as being a resulting output light formed from the interference of output lights Out0, Out1, Out2, Out3 and Out4.

FIG. 10 is a diagram illustrating interference between reflections produced by a VIPA, according to an embodiment of the present invention. Referring now to FIG. 10, light travelling from focal line 78 is reflected by reflecting surface 124. As previously described, reflecting surface 124 has a reflectance of approximately 100% and, therefore, functions essentially as a mirror. As a result, output light Out1 can be optically analyzed as if reflecting surfaces 122 and 124 did not exist and, instead, output light Out1 was emitted from a focal line  $I_1$ . Similarly, output lights Out2, Out3 and Out4 can be optically analyzed as if they were emitted from focal lines  $I_1$ ,  $I_2$ ,  $I_3$  and  $I_4$ , respectively. The focal lines  $I_2$ ,  $I_3$  and  $I_4$  are virtual images of a focal line  $I_0$ .

Therefore, as illustrated in FIG. 10, focal line  $I_1$  is a distance  $2t$  from focal line  $I_0$ , where  $t$  equals the distance between reflecting surfaces 122 and 124. Similarly, each subsequent focal line is a distance  $2t$  from the immediately preceding focal line. Thus, focal line  $I_2$  is a distance  $2t$  from focal line  $I_1$ . Moreover, each subsequent multiple reflection between reflecting surfaces 122 and 124 produces an output light which is weaker in intensity than the previous output light. Therefore, output light Out2 is weaker in intensity than output light Out1.

As illustrated in FIG. 10, output lights from the focal lines overlap and interfere with each other. More specifically, since focal lines  $I_1$ ,  $I_2$ ,  $I_3$  and  $I_4$  are the virtual images of focal line  $I_0$ , output lights Out0, Out1, Out2, Out3 and Out4 have the same optical phase at the positions of focal lines  $I_1$ ,  $I_2$ ,  $I_3$  and  $I_4$ . Therefore, interference produces a luminous flux which travels in a specific direction depending on the wavelength of input light 77.

A VIPA according to the above embodiments of the present invention has strengthening conditions which are characteristics of the design of the VIPA. The strengthening conditions increase the interference of the output lights so that a luminous flux is formed. The strengthening conditions of the VIPA are represented by the following Equation (1):

$$2t \times \cos\phi = m\lambda$$

where  $\phi$  indicates the propagation direction of the resulting luminous flux as measured from a line perpendicular to the surface of reflecting surfaces 122 and 124,  $\lambda$  indicates the wavelength of the input light,  $t$  indicates the distance between the reflecting surfaces 122 and 124, and  $m$  indicates an integer.

Therefore, if  $t$  is constant and  $m$  is assigned a specific value, then the propagation direction  $\phi$  of the luminous flux formed for input light having wavelength  $\lambda$  can be determined.

More specifically, input light 77 is radially dispersed from focal line 78 through a specific angle. Therefore, input light having the same wavelength will be travelling in many different direction from focal line 78, to be reflected between reflecting surfaces 122 and 124. The strengthening conditions of the VIPA cause light travelling in a specific direction to be strengthened through interference of the output lights to form a luminous flux having a direction corresponding to the wavelength of the input light. Light travelling in different direction than the specific direction required by the strengthening condition will be weakened by the interference of the output lights.

FIG. 11 is a diagram illustrating a cross-section along lines IX-IX of the VIPA illustrated in FIG. 7, showing characteristics of a VIPA for determining the angle of incidence, or tilt angle, of input light, according to an embodiment of the present invention.

Referring now to FIG. 11, input light 77 is collected by a cylindrical lens (not illustrated) and focused at focal line 78. As illustrated in FIG. 11, input light 77 covers an area having a width equal to "a" on radiation window 126. After input light

77 is reflected one time from reflecting surface 122, input light 77 is incident on reflecting surface 124 and covers an area having a width equal to "b" on reflecting surface 124. Moreover, as illustrated in FIG. 11, input light 77 travels along optical axis 132 which is at a tilt angle  $\theta_1$  with respect to the normal to reflecting surface 122.

The tilt angle  $\theta_1$  should be set to prevent input light 77 from travelling out of the plate through radiation window 126 after being reflected the first time by reflecting surface 122.

In other words, the tilt angle  $\theta_1$  should be set so that input light 77 remains "trapped" between reflecting surfaces 122 and 124 and does not escape through radiation window 126. Therefore, to prevent input light 77 from travelling out of the plate through radiation window 126, the tilt angle  $\theta_1$  should be set in accordance with the following Equation (2):

$$\text{tilt of optical axis } \theta_1 \geq (a + b) / 4t$$

Therefore, as illustrated by FIGS. 7-11, embodiments of the present invention include a VIPA which receives an input light having a respective wavelength within a continuous range of wavelengths. The VIPA causes multiple reflection of the input light to produce self-interference and thereby form an output light. The output light is spatially distinguishable from an output light formed for an input light having any other wavelength within the continuous range of wavelengths. For example, FIG. 9 illustrates an input light 77 which experiences multiple reflection between reflecting surfaces 122 and 124.



This multiple reflection produces a plurality of output lights Out0, Out1, Out2, Out3 and Out 4 which interfere with each other to produce a spatially distinguishable luminous flux for each wavelength of input light 77.

5        "Self-interference" is a term indicating that interference occurs between a plurality of lights or beams which all originate from the same source. Therefore, the interference of output lights Out0, Out1, Out2, Out3 and Out4 is referred to as self-interference of input light 77, since output lights Out0, Out1,  
10       Out2, Out3 and Out4 all originate from the same source (that is, input light 77).

According to the above embodiments of the present invention, an input light can be at any wavelength within a continuous range of wavelengths. Thus, the input light is not limited to being  
15       a wavelength which is a value chosen from a range of discrete values. In addition, according to the above embodiments of the present invention, the output light produced for an input light at a specific wavelength within a continuous range of wavelengths is spatially distinguishable from an output light which would  
20       have been produced if the input light was at a different wavelength within the continuous range of wavelengths. Therefore, as illustrated, for example, in FIG. 7, the travelling direction (that is, a "spatial characteristic") of the luminous flux 82 is different when input light 77 is at different  
25       wavelengths within a continuous range of wavelengths.

FIGS. 12(A), 12(B), 12(C) and 12(D) are diagram illustrating a method for producing a VIPA, according to an embodiment of the present invention.

Referring now to FIG. 12(A), a parallel plate 164 is preferably made of glass and exhibits excellent parallelism. Reflecting films 166 and 168 are formed on both sides of the parallel plate 164 by vacuum deposition, ion sputtering or other such methods. One of reflecting films 166 and 168 has a reflectance of nearly 100%, and the other reflecting film has a reflectance of lower than 100%, and preferably higher than 80%.

Referring now to FIG. 12(B), one of reflecting films 166 and 168 is partially shaved off to form a radiation window 170. In FIG. 12(B), reflecting film 166 is shown as being shaved off so that radiation window 170 can be formed on the same surface of parallel plate 164 as reflecting film 166. However, instead, reflecting film 168 can be partially shaved off so that a radiation window is formed on the same surface of parallel plate 164 as reflecting film 168. As illustrated by the various embodiment of the present invention, a radiation window can be on either side of parallel plate 164.

Shaving off a reflecting film can be performed by an etching process, but a mechanical shaving process can also be used and is less expensive. However, if a reflecting film is mechanically shaved, parallel plate 164 should be carefully processed to minimize damage to parallel plate 164. For example, if the portion of parallel plate 164 forming the radiation window is severely damaged, parallel plate 164 will generate excess loss caused by scattering of received input light.

Instead of first forming a reflecting film and then shaving it off, a radiation window can be produced by preliminarily masking a portion of parallel plate 164 corresponding to a radiation window, and then protecting this portion from being covered with reflecting film.

Referring now to FIG. 12(C), a transparent adhesive 172 is applied onto reflecting film 166 and the portion of parallel plate 164 from which reflecting film 166 has been removed. Transparent adhesive 172 should generate the smallest possible optical loss since it is also applied to the portion of parallel plate 164 forming a radiation window.

Referring now to FIG. 12(D), a transparent protector plate 174 is applied onto transparent adhesive 172 to protect reflecting film 166 and parallel plate 164. Since transparent adhesive 172 is applied to fill the concave portion generated by removing reflecting film 166, transparent protector plate 174 can be provided in parallel with the top surface of parallel plate 164.

Similarly, to protect reflecting film 168, an adhesive (not illustrated) can be applied to the top surface of reflecting film 168 and should be provided with a protector plate (not illustrated). If reflecting film 168 has a reflectance of about 100%, and there is no radiation window on the same surface of parallel plate 164, then an adhesive and protector plate do not necessarily have to be transparent.

Furthermore, an anti-reflection film 176 can be applied on transparent protector plate 174. For example, transparent protector plate 174 and radiation window 170 can be covered with anti-reflection film 176.

5           According to the above embodiments of the present invention, a focal line is described as being on the surface of a radiation window or on the opposite surface of a parallel plate from which input light enters. However, the focal line can be in the parallel plate, or before the radiation window.

10           According to the above embodiments of the present invention, two reflecting films reflect light therebetween, with the reflectance of one reflecting film being approximately 100%. However, a similar effect can be obtained with two reflecting films each having a reflectance of less than 100%. For example,  
15 both reflecting films can have a reflectance of 95%. In this case, each reflecting film has light travelling therethrough and causing interference. As a result, a luminous flux traveling in the direction depending on the wavelength is formed on both sides of the parallel plate on which the reflecting films are formed.  
20 Thus, the various reflectances of the various embodiments of the present invention can easily be changed in accordance with required characteristics of a VIPA.

          According to the above embodiments of the present invention, a waveguide device is described as being formed by a parallel  
25 plate, or by two reflecting surfaces in parallel with each other. However, the plate or reflecting surfaces do not necessarily have to be parallel.

According to the above embodiments of the present invention, a VIPA uses multiple-reflection and maintains a constant phase difference between interfering lights. As a result, the characteristics of the VIPA are stable, thereby reducing optical characteristic changes caused by polarization. By contrast, the optical characteristics of a conventional diffraction grating experience undesirable changes in dependence on the polarization of the input light.

The above embodiments of the present invention are described as providing luminous fluxes which are "spatially distinguishable" from each other. "Spatially distinguishable" refers to the luminous fluxes being distinguishable in space. For example, various luminous fluxes are spatially distinguishable if they are collimated and travel in different directions, or are focused in different locations. However, the present invention is not intended to be limited to these precise examples, and there are many other ways in which luminous fluxes can be spatially distinguished from each other.

FIG. 13 is a diagram illustrating an apparatus which uses a VIPA as an angular dispersive component, instead of using diffraction gratings, to produce chromatic dispersion, according to an embodiment of the present invention. Referring now to FIG. 13, a VIPA 240 has a first surface 242 with a reflectivity of, for example, approximately 100%, and a second surface 244 with a reflectivity of, for example, approximately 98%. VIPA 240 also includes a radiation window 247. However, VIPA 240 is not intended to be limited to this specific configuration. Instead, VIPA 240 can have many different configurations as described

herein.

As illustrated in FIG. 13, a light is output from a fiber 246, collimated by a collimating lens 248 and line-focused into VIPA 240 through radiation window 247 by a cylindrical lens 250.

5 VIPA 240 then produces a collimated light 251 which is focused by a focusing lens 252 onto a mirror 254. Mirror 254 can be a mirror portion 256 formed on a substrate 258.

Mirror 254 reflects the light back through focusing lens 252 into VIPA 240. The light then undergoes multiple reflections in  
10 VIPA 240 and is output from radiation window 247. The light output from radiation window 247 travels through cylindrical lens 250 and collimating lens 248 and is received by fiber 246.

Therefore, light is output from VIPA 240 and reflected by mirror 254 back into VIPA 240. The light reflected by mirror 254  
15 travels through the path which is exactly opposite in direction to the path through which it originally travelled. As will be seen in more detail below, different wavelength components in the light are focused onto different positions on mirror 254, and are reflected back to VIPA 240. As a result, different wavelength  
20 components travel different distances, to thereby produce chromatic dispersion.

FIG. 14 is a more detailed diagram illustrating the operation of the VIPA in FIG. 13, according to an embodiment of the present invention. Assume a light having various wavelength  
25 components is received by VIPA 240. As illustrated in FIG. 14, VIPA 240 will cause the formation of virtual images 260 of beam waist 262, where each virtual image 260 emits light.

As illustrated in FIG. 14, focusing lens 252 focuses the different wavelength components in a collimated light from VIPA 240 at different points on mirror 254. More specifically, a longer wavelength 264 focuses at point 272, a center wavelength 266 focuses at point 270, and a shorter wavelength 268 focuses at point 274. Then, longer wavelength 264 returns to a virtual image 260 which is closer to beam waist 262, as compared to center wavelength 266. Shorter wavelength 268 returns to a virtual image 260 which is farther from beam waist 262, as compared to center wavelength 266. Thus, the arrangement provides for normal dispersion.

Mirror 254 is designed to reflect only light in a specific interference order, and light in any other interference order should be focused out of mirror 254. More specifically, as previously described, a VIPA will output a collimated light. This collimated light will travel in a direction in which the path from each virtual image has a difference of  $m\lambda$ , where  $m$  is an integer. The  $m$ th order of interference is defined as an output light corresponding to  $m$ .

For example, FIG. 15 is a diagram illustrating various orders of interference of a VIPA. Referring now to FIG. 15, a VIPA, such as VIPA 240, emits collimated lights 276, 278 and 280. Each collimated light 276, 278 and 280 corresponds to a different interference order. Therefore, for example, collimated light 276 is collimated light corresponding to an  $(n+2)$ th interference order, collimated light 278 is collimated light corresponding to an  $(n+1)$ th interference order, and collimated light 280 is collimated light corresponding to an  $n$ th interference order,

wherein  $n$  is an integer. Collimated light 276 is illustrated as having several wavelength components 276a, 276b and 276c. Similarly, collimated light 278 is illustrated as having wavelength components 278a, 278b and 278c, and collimated light 280 is illustrated as having wavelength components 280a, 280b and 280c. Here, wavelength components 276a, 278a and 280a have the same wavelength. Wavelength components 276b, 278b and 280b have the same wavelength (but different from the wavelength of wavelength components 276a, 278a and 280a). Wavelength components 276c, 278c and 280c have the same wavelength (but different from the wavelength of wavelength components 276a, 278a and 280a, and the wavelength of wavelength components 276b, 278b and 280b). Although FIG. 15 only illustrates collimated light for three different interference orders, collimated lights will be emitted for many other interference orders.

Since collimated lights at the same wavelength for different interference orders travel in different directions and are therefore focused at different positions, mirror 254 can be made to reflect only light from a single interference order back into VIPA 240. For example, as illustrated in FIG. 15, the length of a reflecting portion of mirror 254 should be made relatively small, so that only light corresponding to a single interference order is reflected. More specifically, in FIG. 15, only collimated light 278 is reflected by mirror 254. In this manner, collimated lights 276 and 278 are focused out of mirror 254.



A wavelength division multiplexed light usually includes many channels. Referring again to FIG. 13, if the thickness  $t$  between first and second surfaces 242 and 244 of VIPA 240 is set at a specific value, the arrangement will be able to simultaneously compensate for dispersion in each channel.

More specifically, each channel has a center wavelength. These center wavelengths are usually spaced apart by a constant frequency spacing. The thickness  $t$  of VIPA 240 between first and second surfaces 242 and 244 should be set so that all of the wavelength components corresponding to the center wavelengths have the same output angle from VIPA 240 and thus the same focusing position on mirror 254. This is possible when the thickness  $t$  is set so that, for each channel, the round-trip optical length through VIPA 240 travelled by the wavelength component corresponding to the center wavelength is a multiple of the center wavelength of each channel. This amount of thickness  $t$  will hereafter be referred to as the "WDM matching free spectral range thickness", or "WDM matching FSR thickness".

Moreover, in this case, the round-trip optical length  $(2nt\cos\theta)$  through VIPA 240 is equal to the wavelength corresponding to the center wavelength in each channel multiplied by an integer for the same  $\theta$  and different integer, where  $n$  is the refractive index of the material between first and second surfaces 242 and 244,  $\theta$  indicates a propagation direction of a luminous flux corresponding to the center wavelength of each channel. More specifically, as previously described,  $\theta$  indicates the small tilt angle of the optical axis of input light (see FIG. 8).

Therefore, all of the wavelength components corresponding to the center wavelengths will have the same output angle from VIPA 240 and thus the same focusing position on mirror 254, if  $t$  is set so that, for the wavelength component corresponding to the center wavelength in each channel,  $2nt\cos\theta$  is an integer multiple of the center wavelength of each channel for the same  $\theta$  and different integer.

For example, a 2 mm physical length in round trip (which is approximately double a 1 mm thickness of VIPA 240) and a refractive index of 1.5 enable all the wavelengths with a spacing of 100 GHz to satisfy this condition. As a result, VIPA 240 can compensate for dispersion in all the channels of a wavelength division multiplexed light at the same time.

Therefore, referring to FIG. 14, with the thickness  $t$  set to the WDM matching FSR thickness, VIPA 240 and focusing lens 252 will cause (a) the wavelength component corresponding to the center wavelength of each channel to be focused at point 270 on mirror 254, (b) the wavelength component corresponding to the longer wavelength component of each channel to be focused at point 272 on mirror 254, and (c) the wavelength component corresponding to the shorter wavelength component of each channel to be focused at point 274 on mirror 254. Therefore, VIPA 240 can be used to compensate for chromatic dispersion in all channels of a wavelength division multiplexed light.

FIG. 16 is a graph illustrating the amount of dispersion of several channels of a wavelength division multiplexed light, in a case when the thickness  $t$  is set to the WDM matching FSR thickness, according to an embodiment of the present invention.

As illustrated in FIG. 16, all the channels are provided with the same dispersion. However, the dispersions are not continuous between the channels. Moreover, the wavelength range for each channel at which VIPA 240 will compensate for dispersion can be set by appropriately setting the size of mirror 254.

If the thickness  $t$  is not set to the WDM matching FSR thickness, different channels of a wavelength division multiplexed light will be focused at different points on mirror 254. For example, if the thickness  $t$  is one-half, one-third or some other fraction of the round trip optical length thickness, then focusing points of two, three, four or more channels may be focused on the same mirror, with each channel being focused at a different focusing point. More specifically, when the thickness  $t$  is one-half the WDM matching FSR thickness, the light from odd channels will focus at the same points on mirror 254, and the light from even channels will focus at the same points on mirror 254. However, the lights from the even channels will be focused at different points from the odd channels.

For example, FIG. 17 is a diagram illustrating different channels being focused at different points on mirror 254. As illustrated in FIG. 17, wavelength components of the center wavelength of even channels are focused at one point on mirror 254, and wavelength components of the center wavelength of odd channels are focused at a different point. As a result, VIPA 240 can adequately compensate for dispersion in all the channels of a wavelength division multiplexed light at the same time.

There are several different ways to vary the value of the dispersion added by a VIPA. For example, FIG. 18 is a diagram illustrating a side view of an apparatus which uses a VIPA to provide variable dispersion to light, according to an embodiment of the present invention. Referring now to FIG. 18, VIPA 240 causes each different interference order to have a different angular dispersion. Therefore, the amount of dispersion added to an optical signal can be varied by rotating or moving VIPA 240 so that light corresponding to a different interference order is focused on mirror 254 and reflected back into VIPA 240.

FIG. 19 is a diagram illustrating a side view of an apparatus which uses a VIPA to provide variable dispersion, according to an additional embodiment of the present invention. Referring now to FIG. 19, the relative distance between focusing lens 252 and mirror 254 is maintained constant, and focusing lens 252 and mirror 254 are moved together relative to VIPA 240. This movement of focusing lens 252 and mirror 254 changes the shift of light returning to VIPA 240 from mirror 254, and thereby varies the dispersion.

FIGS. 20(A) and 20(B) are diagrams illustrating side views of apparatuses which use a VIPA to provide various values of chromatic dispersion to light, according to additional embodiments of the present invention. FIGS. 20(A) and 20(B) are similar to FIG. 14, in that FIGS. 20(A) and 20(B) illustrate the travel directions of a longer wavelength 264, a center wavelength 266 and a shorter wavelength 268 of light emitted by a virtual image 260 of beam waist 262.

Referring now to FIG. 20(A), mirror 254 is a convex mirror. With a convex mirror, the beam shift is magnified. Therefore, a large chromatic dispersion can be obtained with a short lens focal length and a small amount of space. When mirror 254 is convex, as in FIG. 20(A), the convex shape can typically only be seen from a side view and cannot be seen when viewed from the top.

Referring now to FIG. 20(B), mirror 254 is a concave mirror. With a concave mirror, the sign of the dispersion is inverted. Therefore, anomalous dispersion can be obtained with a short lens focal length and a small space. When mirror 254 is concave, as in FIG. 20(B), the concave shape can typically only be seen from a side view and cannot be seen when viewed from the top.

Therefore, typically, mirror 254 would appear flat in the top view. However, it is possible for mirror 254 to also be a concave or a convex mirror when viewed by the top, thereby indicating that the mirror is a "one-dimensional" mirror.

In FIGS. 20(A) and 20(B), mirror 254 is located at or near the focal point of focusing lens 252.

Therefore, as described above, mirror 254 can be convex or concave in the side view, as illustrated, for example, in FIGS. 20(A) and 20(B), respectively. A convex mirror can enhance the chromatic dispersion and a concave mirror can reduce or even invert the chromatic dispersion from negative (normal) to positive (anomalous). More specifically, a convex mirror generates larger dispersion in the negative direction and a concave mirror generates smaller dispersion in the negative direction or dispersion inverted to positive. This is possible

because the magnitude of chromatic dispersion is a function of the curvature of the mirror in the side view.

FIG. 21 is a graph illustrating the output angle of a luminous flux from VIPA 240 versus wavelength of the luminous flux. As can be seen from FIG. 21, a curve 282 of the wavelength versus the output angle is not linear.

Since the relationship between the wavelength and the output angle of a luminous flux produced by a VIPA is not linear, the chromatic dispersion is not constant in a wavelength band as long as a flat mirror, a normal convex mirror or a normal concave mirror is used as mirror 254. This nonlinearity in chromatic dispersion is referred to as the higher order dispersion.

Generally, referring to the apparatuses in FIGS. 20(A) and 20(B), the nonlinearity in chromatic dispersion can be understood by referring to the following Equation (3):

$$(\text{angular dispersion}) \cdot (1 - f \cdot (1/R)) \propto \text{chromatic dispersion},$$

where  $f$  is the focal length of lens 252 and  $R$  is the radius of curvature of mirror 254.

FIG. 22 is a graph illustrating the angular dispersion of VIPA 240 versus the wavelength of a luminous flux. Generally, the curve 284 in FIG. 22 represents the slope of curve 282 in FIG. 21. As can be seen from FIG. 22, the angular dispersion is not constant. Instead, the angular dispersion changes as the wavelength changes.

FIG. 23 is a graph illustrating the term  $(1-f \cdot (1/R))$  in Equation 3, above, versus wavelength. More specifically, line 286 represents a graph of the term  $(1-f \cdot (1/R))$  versus wavelength for a flat mirror (radius of curvature equals " $\infty$ " (infinity)).  
5 Line 288 represents a graph of the term  $(1-f \cdot (1/R))$  versus wavelength for a concave mirror (radius of curvature equals "+").  
Line 290 represents a graph of the term  $(1-f \cdot (1/R))$  versus wavelength for convex mirror (radius of curvature equals "-").  
As illustrated in FIG. 23, each of the mirrors has a constant  
10 radius of curvature.

FIG. 24 is a diagram illustrating the chromatic dispersion versus wavelength of an apparatus such as in FIGS. 20(A) and 20(B), when mirror 254 is a convex mirror, a flat mirror and a concave mirror. More specifically, curve 292 is a curve of the  
15 chromatic dispersion versus wavelength when mirror 254 is a convex mirror. Curve 294 is a curve of the chromatic dispersion versus wavelength when mirror 254 is a flat mirror. Curve 296 is a curve of the chromatic dispersion versus wavelength when mirror 254 is a concave mirror.

20 In a very general manner, curves 292, 294 and 296 each represent a product of the angular dispersion illustrated in FIG. 22 with the appropriate line illustrated in FIG. 23, as indicated by Equation 3, above. More specifically, generally, curve 292 represents a product of curve 284 in FIG. 22 and line 290 in FIG.  
25 23. Generally, curve 294 represents a product of curve 284 in FIG. 22 and line 286 in FIG. 23. Generally, curve 296 represents a product of curve 284 in FIG. 22 and line 288 in FIG. 23.

As can be seen from FIG. 24, the chromatic dispersion is not constant whether a convex, flat or concave mirror is used as mirror 254.

According to embodiments of the present invention, this wavelength dependence of chromatic dispersion can be reduced or eliminated by chirping the curvature of mirror 254.

More specifically, FIG. 25 is a graph illustrating a curve of the term  $(1-f \cdot (1/R))$  in Equation 3, above, versus wavelength. Generally, curve 298 in FIG. 25 is inverse to curve 284 in FIG. 22. Therefore, a mirror having the characteristics in FIG. 25 will provide a constant chromatic dispersion, as illustrated by the curve 300 in FIG. 26.

For example, with the apparatus illustrated, for example, in FIG. 14, a longer wavelength has a larger dispersion in the negative direction than a shorter wavelength. Therefore, mirror 254 can be designed to have a concave portion where the longer wavelength reflects, and a convex portion where the shorter wavelength reflects, to effectively cancel the wavelength dependence of dispersion. Ideally, the curvature of mirror 254 varies from convex to concave continuously along the focusing point of light when the wavelength changes from short to long. If this modification is based on a conventional convex mirror, not a flat mirror, the curvature of the mirror can be made to vary from strong convex to weak convex continuously along the focusing point of light when the wavelength changes from short to long.



Therefore, there are many different designs for mirror 254, to provide a constant chromatic dispersion. For example, FIG. 27 is a graph illustrating characteristics many different mirror designs, according to embodiments of the present invention.

5 Curve 302 in FIG. 27 illustrates a mirror which continuously changes from convex to concave as the wavelength of output light increases. Curve 304 illustrates a mirror which changes from strongly convex to slightly convex as the wavelength of output light increases. Curve 306 illustrates a mirror which changes  
10 from slightly concave to strongly concave as the wavelength of output light increases. Other mirror designs include, for example, those shown by curves 308 and 310.

There are a virtually unlimited number of mirror designs which could be used, and such designs could be graphed in FIG.  
15 27. Moreover, mirror designs are not intended to be limited to those having characteristic curves with the same slopes as those in FIG. 27.

FIGS. 28(A), 28(B), 28(C) and 28(D) illustrate the surface shape of various mirrors which can be used as mirror 254,  
20 according to embodiments of the present invention. For example, FIG. 28(A) illustrates a mirror which continuously changes from convex to concave, as represented by curve 302 in FIG. 27. FIG. 28(B) illustrates a mirror which continuously changes from strong convex to weak convex, as represented by curve 310 in FIG. 27.  
25 FIG. 28(C) illustrates a mirror which continuously changes from weak concave to strong concave, as represented by curve 306 in FIG. 27.

Moreover, there are a virtually unlimited number of mirror designs which could be used. For example, FIG. 28(D) illustrates a flat mirror which changes to convex. FIG. 27(E) illustrates a flat mirror which changes to concave. FIG. 28(F) illustrates a mirror having a convex portion and a concave portion, but where the mirror does not continuously change from convex to concave.

Therefore, according to the above embodiments of the present invention, an apparatus includes a VIPA, a mirror and a lens. The VIPA receives an input light and produces a corresponding output light (such as a luminous flux) propagating away from the VIPA. The lens focuses the output light onto the mirror so that the mirror reflects the output light and the reflected light is directed by the lens back to the VIPA. The mirror has a shape which causes the apparatus to produce a constant chromatic dispersion.

For example, output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes. The mirror is shaped so that the surface points change continuously from convex to concave as the wavelength of the output light changes from shorter to longer. As another example, the mirror can be shaped so that the surface points change continuously from stronger convex to weaker convex as the wavelength of the output light changes from shorter to longer. Alternatively, the mirror can be shaped so that the surface points change continuously from weaker concave to stronger concave as the wavelength of the output light changes from shorter to longer. There are many other examples. For example, the mirror can have a concave portion and a convex

portion so that output light at a shorter wavelength than a specific wavelength reflects off the convex portion and so that output light at a longer wavelength than the specific wavelength reflect off the concave portion.

5           Moreover, for example, the mirror can have a flat portion which continuously changes to a concave portion in correspondence with an increase in the wavelength of the output light above a specific wavelength so that output light at a shorter wavelength than the specific wavelength is incident on the flat portion and  
10           output light at a longer wavelength than the specific wavelength is incident on the concave portion. Or, the mirror can have a convex portion which continuously changes to a flat portion in corresponding with an increase in the wavelength of the output light above a specific wavelength so that output light at a  
15           shorter wavelength than the specific wavelength is incident on the convex portion and output light at a longer wavelength than the specific wavelength is incident on the flat portion.

FIG. 29 is a diagram illustrating a side view of an apparatus which uses a VIPA to provide variable dispersion to  
20           light, according to a further embodiment of the present invention. Referring now to FIG. 29, focusing lens 252 and mirror 254 are replaced with a retroreflector 312. Preferably, retroreflector 312 has two or three reflecting surfaces and reflects incident light in the opposite direction from the  
25           propagation direction of the incident light. The use of retroreflector 312 will cause the VIPA-retroreflector arrangement to add anomalous dispersion. Moreover, retroreflector 312 is movable with respect to VIPA 240, to vary the amount of

dispersion.

FIG. 30 is a diagram illustrating a top view of the apparatus in FIG. 13, combined with a circulator, according to an embodiment of the present invention. Referring now to FIG. 30, a circulator 314 receives input light from an input fiber 316 and provides the input light to collimating lens 248. Output light reflected by mirror 254 and back through VIPA 240 is received by circulator 314 and provided to an output fiber 318. In FIG. 30, focusing lens 252 is a "normal" focusing lens, where a "normal" focusing lens refers to a focusing lens which focuses light as seen from both a top view and a side view of the focusing lens, and has the same focal length in the top and side view.

FIG. 31 is a diagram illustrating a top view of an apparatus which uses a VIPA to add dispersion to light, according to an additional embodiment of the present invention. Referring now to FIG. 31, a cylindrical lens 320 line-focuses light output from VIPA 240 to mirror 254. Mirror 254 is slightly tilted when viewed from the top (as in FIG. 23). Input fiber 316 provides input light to collimating lens 248, and output fiber 318 receives light reflected by mirror 254 and back through VIPA 240. Therefore, by using cylindrical lens 320 and tilting mirror 254, it is not necessary to use a circulator (such as circulator 314 illustrated in FIG. 30).

However, there are several disadvantages of the apparatuses in FIGS. 30 and 31. Regarding the apparatus in FIG. 30, circulator 314 is required to separate the input light from the output light. However, a circulator will produce some undesirable

optical loss. In addition, a circulator can be too large in physical size for many situations.

Regarding the apparatus in FIG. 31, the performance of the apparatus is relatively low since the input light received by VIPA 240 is not perpendicular to VIPA 240 as seen from the top view in FIG. 31. More specifically, since the input light received by VIPA 240 is not perpendicular to VIPA 240, the various output lights (such as, for example, output lights Out 1, Out2, Out 3 in FIG. 9) will not completely overlap. Instead, the output lights will only partially overlap, thereby decreasing performance of the apparatus.

FIG. 32 is a diagram illustrating a top view of an apparatus which uses a VIPA to add dispersion to light, and which eliminates some of the disadvantages of the apparatuses illustrated in FIGS. 30 and 31, according to an additional embodiment of the present invention.

Referring now to FIG. 32, a collimating lens 322a and a semi-cylindrical lens 324a are positioned between input fiber 316 and VIPA 240. Input light travels from input fiber 316 and is formed into a collimated light by collimating lens 322a. This collimated light is then line focused by semi-cylindrical lens 324a into the radiation window of VIPA 240. A resulting luminous flux produced by VIPA 240 travels to focusing lens 252 and is focused onto mirror 254, to be reflected by mirror 254. In FIG. 32, focusing lens 252 is a "normal" focusing lens, where "normal" focusing lens refers to a focusing lens which focuses light as seen from both a top view and a side view of the focusing lens, and has the same focal length in the top and side views.

A collimating lens 322b and a semi-cylindrical lens 324b are positioned between output fiber 318 and VIPA 240. The light reflected by mirror 254 back to VIPA 240 undergoes multiple reflection inside VIPA 240 and is output through the radiation window of VIPA 240. This output light from VIPA 240 travels to semi-cylindrical lens 324b and collimating lens 322b, to be focused into output fiber 318.

As illustrated in FIG. 32, the light which is focused on mirror 254 is not perpendicular to mirror 254 in the top view. This occurs since focusing lens 252 is placed so that the luminous flux produced by VIPA 240 does not pass through the center of focusing lens 252 in the top view. Similarly, the light reflected by mirror 254 does not pass through the center of focusing lens 252. Preferably, the lens center of focusing lens 252 is displaced from the beam center of the luminous flux produced by VIPA 240 and the beam center of the light reflected by mirror 254 by at least half the beam thickness in the top view. As a result, focusing lens 252 focuses light on mirror 254 at the position of the extended lens axis 326 of focusing lens 252. Further, light 328 travelling from VIPA 240 to focusing lens 252 will be parallel to light 330 travelling from focusing lens 252 to VIPA 240 for any wavelength.

With the apparatus illustrated in FIG. 32, the input light from input fiber 316 travels in a different space than the output light to be received by output fiber 318. Thus, the output light can be coupled to a fiber which is different from the input fiber, and a circulator is not required. Moreover, the apparatus has a relatively high performance since the input light received

into the radiation window of VIPA 240 travels in a perpendicular direction to VIPA 240, as seen in a top view.

While FIG. 32 illustrates two separate semi-cylindrical lenses 324a and 324b, a single semi-cylindrical lens can be used. For example, FIG. 33 is a diagram illustrating a single semi-cylindrical lens 324 used instead of plural semi-cylindrical lenses 324a and 324b, according to an embodiment of the present invention.

Further, generally, a semi-cylindrical lens is defined as a lens which focuses light in one of a top view of a side view, and has no focusing effect in the other view. Semi-cylindrical lenses are well-known.

In addition, the present invention is not intended to be limited to the use of collimating lenses, semi-cylindrical lenses and/or any other specific type of lens. Instead, many other lenses or devices can be used as long as the appropriate effect is provided.

Therefore, as illustrated, for example, in FIG. 32, an apparatus includes a VIPA (such as, for example, VIPA 240), a light returning device (such as, for example, mirror 254) and a lens (such as, for example, focusing lens 252). The VIPA receives an input light and produces a corresponding output light (for example, a luminous flux) propagating away from the VIPA. The light returning device receives the output light from the VIPA and then returns the output light back to the VIPA. The lens is positioned so that (a) the output light travels from the VIPA to the light returning device by travelling from the VIPA to the lens and then being focused by the lens to the light

returning device, (b) the output light returns from the light returning device to the VIPA by travelling from the light returning device to the lens and then being directed by the lens to the VIPA, and (c) the output light travelling from the VIPA to the lens is parallel with the returned output light travelling from the lens to the VIPA.

A VIPA, according to the above embodiments of the present invention, provides a much larger angular dispersion than a diffraction grating. Therefore, a VIPA as described herein can be used to compensate for much larger chromatic dispersion than a spatial grating pair arrangement as illustrated in FIGS. 6(A) and 6(B).

In the above embodiments of the present invention, a mirror is used to reflect light back into VIPA 240. Thus, a mirror can be referred to as a "light returning device" which returns light back to VIPA 240. However, the present invention is not intended to be limited to the use of a mirror as a light returning device. For example, a prism (instead of a mirror) can be used as a light returning device to return light back to VIPA 240. Moreover, various combinations of mirrors and/or prisms, or lens apparatuses can be used as a light returning device to return light back to VIPA.

In the above embodiments of the present invention, a VIPA has reflecting films to reflect light. For example, FIG. 8 illustrates a VIPA 76 having reflecting films 122 and 124 to reflect light. However, it is not intended for a VIPA to be limited to the use of "film" to provide a reflecting surface. Instead, the VIPA must simply have appropriate reflecting



surfaces, and these reflecting surfaces may or may not be formed by "film".

Further, in the above embodiments of the present invention, a VIPA includes a transparent glass plate in which multiple reflection occurs. For example, FIG. 8 illustrates a VIPA 76 having a transparent glass plate 120 with reflecting surfaces thereon. However, it is not intended for a VIPA to be limited to the use of a glass material, or any type of "plate", to separate the reflecting surfaces. Instead, the reflecting surfaces must simply be maintained to be separated from each other by some type of spacer. For example, the reflecting surfaces of a VIPA can be separated by "air", without having a glass plate therebetween. Therefore, the reflecting surfaces can be described as being separated by a transparent material which is, for example, optical glass or air.

As described above, the operation of a VIPA is sensitive to the thickness and the refractive index of the material between the reflecting surfaces of the VIPA. In addition, the operational wavelength of a VIPA can be precisely adjusted by controlling the temperature of the VIPA.

More specifically, FIG. 34 is a diagram illustrating a controller for controlling the temperature of a VIPA, according to an embodiment of the present invention. Referring now to FIG. 34, a VIPA 340 produces an output light 342. A temperature sensor 344 detects the temperature of VIPA 340. Based on the detected temperature, a controller 346 controls a heating/cooling element 348 to control the temperature of VIPA 340 to adjust the operational wavelength of VIPA 340.

For example, raising and lowering the temperature of VIPA 340 can slightly change the output angle of output light 342. Moreover, an output light corresponding to a specific wavelength of input light should be output from VIPA 340 at a precise output angle. Therefore, controller 346 adjusts the temperature of VIPA 340 so that output light 342 is properly output at the correct output angle, and remains stable.

According to the above embodiments of the present invention, an apparatus uses a VIPA to compensate for chromatic dispersion. For this purpose, the embodiments of the present invention are not intended to be limited to a specific VIPA configuration. Instead, any of the different VIPA configurations discussed herein, or those disclosed in related U.S. application number 08/685,362, which is incorporated herein by reference, can be used in an apparatus to compensate for chromatic dispersion. For example, the VIPA may or may not have a radiation window, and the reflectances on the various surfaces of the VIPA are not intended to be limited to any specific examples.

Although a few preferred embodiments of the present invention have been shown and described, it would be appreciated by those skilled in the art that changes may be made in these embodiments without departing from the principles and spirit of the invention, the scope of which is defined in the claims and their equivalents.

CLAIMS

What is claimed is:

1. An apparatus comprising:

a virtually imaged phased array (VIPA) which receives an input light and produces a corresponding output light propagating away from the VIPA;

a light returning device which receives the output light from the VIPA and then returns the output light back to the VIPA; and

a lens positioned so that

the output light travels from the VIPA to the light returning device by travelling from the VIPA to the lens and then being focused by the lens to the light returning device,

the output light returns from the light returning device to the VIPA by travelling from the light returning device to the lens and then being directed by the lens to the VIPA, and

the output light travelling from the VIPA to the lens is parallel with, travels in the opposite direction to, and does not overlap with, the returned output light travelling from the lens to the VIPA.

2. An apparatus as in claim 1, further comprising:

first and second optical fibers, wherein

the input light travels through the first optical fiber to be received in the VIPA, and,

after being returned to the VIPA, the output light undergoes multiple reflection in the VIPA and is then received by the second optical fiber.

1 3. An apparatus as in claim 2, further comprising:  
2 a first lens which directs the input light from the first  
3 optical fiber to the VIPA; and  
4 a second lens which directs the returned output light from  
5 the VIPA to the second optical fiber.

1 4. An apparatus as in claim 2, further comprising:  
2 a lens which directs the input light from the first optical  
3 fiber to the VIPA, and which directs the returned output light  
4 from the VIPA to the second optical fiber.

1 5. An apparatus as in claim 1, wherein the light returning  
2 device is a mirror.

1 6. An apparatus as in claim 1, wherein the output light  
2 travelling from the VIPA passes through the lens and focuses on  
3 the mirror so that the light incident on the mirror is not  
4 perpendicular to the mirror surface.

1 7. An apparatus as in claim 1, wherein the lens is positioned  
2 so that

3 the output light travelling from the VIPA to the lens  
4 passes off center through of the lens, and

5 the returned output light travelling from the lens to  
6 the VIPA passes off center through the lens.

1 8. An apparatus comprising:

2 an angular dispersive component having a passage area to  
3 receive light into, and to output light from, the angular  
4 dispersive component, the angular dispersive component receiving,  
5 through the passage area, an input light having a respective  
6 wavelength within a continuous range of wavelengths, and causing  
7 multiple reflection of the input light to produce  
8 self-interference that forms an output light travelling from the  
9 angular dispersive component and which is spatially  
10 distinguishable from an output light formed for an input light  
11 having any other wavelength within the continuous range of  
12 wavelengths;

13 a light returning device which receives the output light  
14 from the angular dispersive component and returns the output  
15 light to the angular dispersive component to undergo multiple  
16 reflection in the angular dispersive component and then be output  
17 from the angular dispersive component through the passage area;  
18 and

19 a lens positioned so that

20 the output light travels from the angular dispersive  
21 component to the light returning device by travelling from the  
22 angular dispersive component to the lens and then being focused  
23 by the lens to the light returning device,

24 the output light returns from the light returning  
25 device to the angular dispersive component by travelling from the  
26 light returning device to the lens and then being directed by the  
27 lens to the angular dispersive component, and

28           the output light travelling from the angular dispersive  
29 component to the lens is parallel with the returned output light  
30 travelling from the lens to the angular dispersive component.

1     9.    An apparatus as in claim 8, further comprising:

2           first and second optical fibers, wherein

3           the input light travels through the first optical fiber  
4 to be received into the angular dispersive component through the  
5 passage area, and,

6           after undergoing multiple reflection in the angular  
7 dispersive component and then being output through the passage  
8 area, the returned output light is received by the second optical  
9 fiber.

1     10.   An apparatus as in claim 9, further comprising:

2           a lens which line focuses the input light from the first  
3 optical fiber into the angular dispersive component through the  
4 passage area; and

5           a lens which directs the returned output light from the  
6 passage area of the angular dispersive component to the second  
7 optical fiber.

1     11.   An apparatus as in claim 9, further comprising:

2           a lens which directs the input light from the first optical  
3 fiber into the angular dispersive component through the passage  
4 area, and which directs the returned output light from the  
5 passage area of the angular dispersive component to the second  
6 optical fiber.

12. An apparatus as in claim 9, further comprising:

a first lens which receives the input light from the first optical fiber and forms a collimated light;

a second lens which receives the collimated light from the first lens and line focuses the collimated light into the passage area of the angular dispersive component;

a third lens which forms collimated light of the returned output light from the passage area of the angular dispersive component; and

a fourth lens which focuses the collimated light from the third lens into the second optical fiber.

13. An apparatus as in claim 8, wherein the light returning device is a mirror.

14. An apparatus comprising:

a virtually imaged phased array (VIPA) which receives an input light and produces a corresponding output light propagating away from the VIPA;

a mirror; and

a lens which focuses the output light onto the mirror so that the mirror reflects the output light, the reflected light being directed by the lens back to the VIPA,

wherein the mirror is shaped so that the apparatus provides a constant chromatic dispersion.

1 15. An apparatus as in claim 14, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror is shaped so that the surface points change  
6 continuously from convex to concave as the wavelength of the  
7 output light changes from shorter to longer.

1 16. An apparatus as in claim 14, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror is shaped so that the surface points change  
6 continuously from stronger convex to weaker convex as the  
7 wavelength of the output light changes from shorter to longer.

1 17. An apparatus as in claim 14, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror is shaped so that the surface points change  
6 continuously from weaker concave to stronger concave as the  
7 wavelength of the output light changes from shorter to longer.



1 18. An apparatus as in claim 14, wherein

2 the mirror has a concave portion and a convex portion so  
3 that output light at a shorter wavelength than a specific  
4 wavelength reflects off the convex portion and output light at  
5 a longer wavelength than the specific wavelength reflects off the  
6 concave portion.

1 19. An apparatus as in claim 14, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror has a flat portion which continuously changes to  
6 a concave portion in correspondence with an increase in the  
7 wavelength of the output light above a specific wavelength so  
8 that output light at a shorter wavelength than the specific  
9 wavelength is incident on the flat portion and output light at  
10 a longer wavelength than the specific wavelength is incident on  
11 the concave portion.

1 20. An apparatus as in claim 14, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror has a convex portion which continuously changes  
6 to a flat portion in correspondence with an increase in the  
7 wavelength of the output light above a specific wavelength so  
8 that output light at a shorter wavelength than the specific  
9 wavelength is incident on the convex portion and output light at

10 a longer wavelength than the specific wavelength is incident on  
11 the flat portion.

1 21. An apparatus comprising:

2 an angular dispersive component having a passage area to  
3 receive light into, and to output light from, the angular  
4 dispersive component, the angular dispersive component receiving,  
5 through the passage area, an input light having a respective  
6 wavelength within a continuous range of wavelengths, and causing  
7 multiple reflection of the input light to produce  
8 self-interference that forms an output light travelling from the  
9 angular dispersive component and which is spatially  
10 distinguishable from an output light formed for an input light  
11 having any other wavelength within the continuous range of  
12 wavelengths;

13 a mirror; and

14 a lens which focuses the output light formed by the angular  
15 dispersive component to the mirror, wherein

16 the mirror reflects the focused light back to the lens  
17 and the lens directs the reflected output light back to the  
18 angular dispersive component so that the reflected output light  
19 undergoes multiple reflection in the angular dispersive component  
20 and is then output from the angular dispersive component through  
21 the passage area, and

22 the mirror is shaped so that the apparatus provides a  
23 constant chromatic dispersion.

1 22. An apparatus as in claim 21, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror is shaped so that the surface points change  
6 continuously from convex to concave as the wavelength of the  
7 output light changes from shorter to longer.

1 23. An apparatus as in claim 21, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror is shaped so that the surface points change  
6 continuously from stronger convex to weaker convex as the  
7 wavelength of the output light changes from shorter to longer.

1 24. An apparatus as in claim 21, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror is shaped so that the surface points change  
6 continuously from weaker concave to stronger concave as the  
7 wavelength of the output light changes from shorter to longer.

1 25. An apparatus as in claim 21, wherein

2 the mirror has a concave portion and a convex portion so  
3 that output light at a shorter wavelength than a specific  
4 wavelength reflects off the convex portion and output light at  
5 a longer wavelength than the specific wavelength reflects off the  
6 concave portion.

1 26. An apparatus as in claim 21, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror has a flat portion which continuously changes to  
6 a concave portion in correspondence with an increase in the  
7 wavelength of the output light above a specific wavelength so  
8 that output light at a shorter wavelength than the specific  
9 wavelength is incident on the flat portion and output light at  
10 a longer wavelength than the specific wavelength is incident on  
11 the concave portion.

1 27. An apparatus as in claim 21, wherein

2 the output light focused by the lens is incident on a  
3 different surface point on the mirror as the wavelength of the  
4 output light changes, and

5 the mirror has a convex portion which continuously changes  
6 to a flat portion in correspondence with an increase in the  
7 wavelength of the output light above a specific wavelength so  
8 that output light at a shorter wavelength than the specific  
9 wavelength is incident on the convex portion and output light at

10 a longer wavelength than the specific wavelength is incident on  
11 the flat portion.

**AMENDED CLAIMS**

[received by the International Bureau on 11 December 1998 (11.12.98);  
original claims 1-4,6-8,14 and 22-24 amended; new claims 28-49 added;  
remaining claims unchanged (21 pages)]

1. An apparatus having a top view and comprising:

a virtually imaged phased array (VIPA) generator which receives an input light and produces a corresponding output light propagating away from the VIPA generator and thereby propagating away from a respective surface of the VIPA generator;

a light returning device which receives the output light from the VIPA generator and then returns the output light back to the VIPA generator, and thereby back to the VIPA generator; and

a lens positioned so that

the output light travels from the VIPA generator to the light returning device by travelling from the VIPA generator to the lens and then being focused by the lens to the light returning device,

the output light returns from the light returning device to the VIPA generator by travelling from the light returning device to the lens and then being directed by the lens to the VIPA generator, and

the output light travelling from the VIPA generator to the lens is perpendicular to said surface of the VIPA generator in the top view, and the returned output light travelling from the lens to the VIPA generator is perpendicular to said surface of the VIPA generator in the top view.

2. An apparatus as in claim 1, further comprising:

first and second optical fibers, wherein

the input light travels through the first optical fiber to be received in the VIPA generator, and,

after being returned to the VIPA generator, the output light undergoes multiple reflection in the VIPA generator and is then received by the second optical fiber.

3. An apparatus as in claim 2, further comprising:

a first lens which directs the input light from the first optical fiber to the VIPA generator; and

a second lens which directs the returned output light from the VIPA generator to the second optical fiber.

4. An apparatus as in claim 2, further comprising:

a lens which directs the input light from the first optical fiber to the VIPA generator, and which directs the returned output light from the VIPA generator to the second optical fiber.

5. An apparatus as in claim 1, wherein the light returning device is a mirror.

6. An apparatus as in claim 5, wherein the output light travelling from the VIPA generator passes through the lens and focuses on the mirror so that the light incident on the mirror is not perpendicular to the mirror surface.

7. An apparatus as in claim 1, wherein the lens is positioned so that  
the output light travelling from the VIPA generator to the lens passes off  
center through of the lens, and  
the returned output light travelling from the lens to the VIPA generator passes  
off center through the lens.

8. An apparatus having a top view and comprising:  
an angular dispersive component having a passage area to receive light into, and to  
output light from, the angular dispersive component, the angular dispersive component  
receiving, through the passage area, an input light having a respective wavelength within a  
continuous range of wavelengths, and causing multiple reflection of the input light to produce  
self-interference that forms an output light travelling from the angular dispersive component  
and thereby travelling from a respective surface of the angular dispersive component, the  
output light being spatially distinguishable from an output light formed for an input light  
having any other wavelength within the continuous range of wavelengths;

a light returning device which receives the output light from the angular dispersive  
component and returns the output light to said surface of the angular dispersive component,  
and thereby to the angular dispersive component, to undergo multiple reflection in the  
angular dispersive component and then be output from the angular dispersive component  
through the passage area; and

a lens positioned so that



the output light travels from the angular dispersive component to the light returning device by travelling from the angular dispersive component to the lens and then being focused by the lens to the light returning device,

the output light returns from the light returning device to the angular dispersive component by travelling from the light returning device to the lens and then being directed by the lens to the angular dispersive component, and

the output light travelling from the angular dispersive component to the lens is perpendicular to said surface of the angular dispersive component in the top view, and the returned output light travelling from the lens to the angular dispersive component is perpendicular to said surface of the angular dispersive component in the top view.

9. An apparatus as in claim 8, further comprising:

first and second optical fibers, wherein

the input light travels through the first optical fiber to be received into the angular dispersive component through the passage area, and,

after undergoing multiple reflection in the angular dispersive component and then being output through the passage area, the returned output light is received by the second optical fiber.

10. An apparatus as in claim 9, further comprising:

a lens which line focuses the input light from the first optical fiber into the angular dispersive component through the passage area; and

a lens which directs the returned output light from the passage area of the angular dispersive component to the second optical fiber.

11. An apparatus as in claim 9, further comprising:

a lens which directs the input light from the first optical fiber into the angular dispersive component through the passage area, and which directs the returned output light from the passage area of the angular dispersive component to the second optical fiber.

12. An apparatus as in claim 9, further comprising:

a first lens which receives the input light from the first optical fiber and forms a collimated light;

a second lens which receives the collimated light from the first lens and line focuses the collimated light into the passage area of the angular dispersive component;

a third lens which forms collimated light of the returned output light from the passage area of the angular dispersive component; and

a fourth lens which focuses the collimated light from the third lens into the second optical fiber.

13. An apparatus as in claim 8, wherein the light returning device is a mirror.

14. An apparatus comprising:
- a virtually imaged phased array (VIPA) which receives an input light and produces a corresponding output light propagating away from the VIPA generator;
- a mirror; and
- a lens which focuses the output light onto the mirror so that the mirror reflects the output light, the reflected light being directed by the lens back to the VIPA generator,
- wherein the mirror is shaped so that the apparatus provides a constant chromatic dispersion.
15. An apparatus as in claim 14, wherein
- the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and
- the mirror is shaped so that the surface points change continuously from convex to concave as the wavelength of the output light changes from shorter to longer.
16. An apparatus as in claim 14, wherein
- the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and
- the mirror is shaped so that the surface points change continuously from stronger convex to weaker convex as the wavelength of the output light changes from shorter to longer.

17. An apparatus as in claim 14, wherein
- the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and
- the mirror is shaped so that the surface points change continuously from weaker concave to stronger concave as the wavelength of the output light changes from shorter to longer.
18. An apparatus as in claim 14, wherein
- the mirror has a concave portion and a convex portion so that output light at a shorter wavelength than a specific wavelength reflects off the convex portion and output light at a longer wavelength than the specific wavelength reflects off the concave portion.
19. An apparatus as in claim 14, wherein
- the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and
- the mirror has a flat portion which continuously changes to a concave portion in correspondence with an increase in the wavelength of the output light above a specific wavelength so that output light at a shorter wavelength than the specific wavelength is incident on the flat portion and output light at a longer wavelength than the specific wavelength is incident on the concave portion.

20. An apparatus as in claim 14, wherein

the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror has a convex portion which continuously changes to a flat portion in correspondence with an increase in the wavelength of the output light above a specific wavelength so that output light at a shorter wavelength than the specific wavelength is incident on the convex portion and output light at a longer wavelength than the specific wavelength is incident on the flat portion.

21. An apparatus comprising:

an angular dispersive component having a passage area to receive light into, and to output light from, the angular dispersive component, the angular dispersive component receiving, through the passage area, an input light having a respective wavelength within a continuous range of wavelengths, and causing multiple reflection of the input light to produce self-interference that forms an output light travelling from the angular dispersive component and which is spatially distinguishable from an output light formed for an input light having any other wavelength within the continuous range of wavelengths;

a mirror; and

a lens which focuses the output light formed by the angular dispersive component to the mirror, wherein

the mirror reflects the focused light back to the lens and the lens directs the reflected output light back to the angular dispersive component so that the reflected output

light undergoes multiple reflection in the angular dispersive component and is then output from the angular dispersive component through the passage area, and  
the mirror is shaped so that the apparatus provides a constant chromatic dispersion.

22. An apparatus as in claim 21, wherein

the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror is shaped so that the respective surface points change continuously from convex to concave as the wavelength of the output light changes from shorter to longer.

23. An apparatus as in claim 21, wherein

the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror is shaped so that the respective surface points change continuously from stronger convex to weaker convex as the wavelength of the output light changes from shorter to longer.

24. An apparatus as in claim 21, wherein

the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror is shaped so that the respective surface points change continuously from weaker concave to stronger concave as the wavelength of the output light changes from shorter to longer.

25. An apparatus as in claim 21, wherein

the mirror has a concave portion and a convex portion so that output light at a shorter wavelength than a specific wavelength reflects off the convex portion and output light at a longer wavelength than the specific wavelength reflects off the concave portion.

26. An apparatus as in claim 21, wherein

the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror has a flat portion which continuously changes to a concave portion in correspondence with an increase in the wavelength of the output light above a specific wavelength so that output light at a shorter wavelength than the specific wavelength is incident on the flat portion and output light at a longer wavelength than the specific wavelength is incident on the concave portion.

27. An apparatus as in claim 21, wherein

the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror has a convex portion which continuously changes to a flat portion in correspondence with an increase in the wavelength of the output light above a specific wavelength so that output light at a shorter wavelength than the specific wavelength is incident on the convex portion and output light at a longer wavelength than the specific wavelength is incident on the flat portion.

28. An apparatus having a top view and comprising:

first and second surfaces, the second surface having a reflectivity which causes a portion of light incident thereon to be transmitted therethrough, where

an input light at a respective wavelength is focused into a line, and

the first and second surfaces are positioned so that the input light radiates from the line to be reflected a plurality of times between the first and second surfaces and thereby cause a plurality of lights to be transmitted through the second surface, the plurality of transmitted lights interfering with each other to produce an output light travelling from the second surface and which is spatially distinguishable from an output light produced for an input light at a different wavelength;

a light returning device which returns the output light to the second surface so that the output light passes through the second surface and undergoes multiple reflection between the first and second surfaces; and

a lens positioned so that



the output light travels from the second surface to the light returning device by travelling from the second surface to the lens and then being focused by the lens to the light returning device,

the output light returns from the light returning device to the second surface by travelling from the light returning device to the lens and then being directed by the lens to the second surface, and

the output light travelling from the second surface to the lens is perpendicular to the second surface in the top view, and the returned output light travelling from the lens to the second surface is perpendicular to the second surface in the top view.

29. An apparatus as in claim 28, wherein the light returning device is a mirror.

30. An apparatus as in claim 29, wherein the output light travelling from the second surface passes through the lens and focuses on the mirror so that the light incident on the mirror is not perpendicular to the mirror surface.

30. An apparatus as in claim 29, wherein the output light travelling from the second surface passes through the lens and focuses on the mirror so that the light incident on the mirror is not perpendicular to the mirror surface.

31. An apparatus having a top view and comprising:

generating means for receiving an input light at a respective wavelength and for producing a corresponding output light propagating away from the generating means in a direction determined by the wavelength of the input light, the output light thereby propagating away from a respective surface of the generating means;

returning means for returning the output light back to the said surface of the generating means, and thereby returning the output light back to the generating means; and

a lens positioned so that

the output light travels from the generating means to the returning means by travelling from the generating means to the lens and then being focused by the lens to the returning means,

the output light returns from the returning means to the generating means by travelling from the returning means to the lens and then being directed by the lens to the generating means, and

the output light travelling from the generating means to the lens is perpendicular to said surface of the generating means in the top view, and the returned output light travelling from the lens to the generating means is perpendicular to said surface of the generating means in the top view.

32. An apparatus receiving an input light at a respective wavelength and focused into a line, the apparatus having a top view and comprising:

first and second surfaces spaced apart from each other;

means for causing the input light to radiate from the line to be reflected a plurality of times between the first and second surfaces and thereby cause a plurality of lights to be transmitted through the second surface, and for causing the transmitted lights to interfere with each other to produce an output light travelling away from the second surface and which is spatially distinguishable from an output light produced for an input light at a different wavelength;

returning means for returning the output light to the second surface so that the returned output light passes through the second surface and undergoes multiple reflection between the first and second surfaces; and

a lens positioned so that

the output light travels from the second surface to the returning means by travelling from the second surface to the lens and then being focused by the lens to the returning means,

the output light returns from the returning means to the second surface by travelling from the returning means to the lens and then being directed by the lens to the second surface, and

the output light travelling from the second surface to the lens is perpendicular to the second surface in the top view, and the returned output light travelling from the lens to the second surface is perpendicular to the second surface in the top view.

33. An apparatus comprising:

an angular dispersive component having a passage area to receive light into, and to output light from, the angular dispersive component, the angular dispersive component receiving, through the passage area, an input light focused into a line and having a respective wavelength, and causing multiple reflection of the input light to produce self-interference that forms an output light travelling from the angular dispersive component and which is spatially distinguishable from an output light formed for an input light having a different wavelength;

a mirror; and

a lens which focuses the output light formed by the angular dispersive component to the mirror, wherein

the mirror reflects the focused light back to the lens and the lens directs the reflected output light back to the angular dispersive component so that the reflected output light undergoes multiple reflection in the angular dispersive component and is then output from the angular dispersive component through the passage area, and

the mirror is shaped so that the apparatus provides a constant chromatic dispersion.

34. An apparatus as in claim 33, wherein

the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror is shaped so that the respective surface points change continuously from convex to concave as the wavelength of the output light changes from shorter to longer.

35. An apparatus as in claim 33, wherein  
the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and  
the mirror is shaped so that the respective surface points change continuously from stronger convex to weaker convex as the wavelength of the output light changes from shorter to longer.
36. An apparatus as in claim 33, wherein  
the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and  
the mirror is shaped so that the respective surface points change continuously from weaker concave to stronger concave as the wavelength of the output light changes from shorter to longer.
37. An apparatus as in claim 33, wherein  
the mirror has a concave portion and a convex portion so that output light at a shorter wavelength than a specific wavelength reflects off the convex portion and output light at a longer wavelength than the specific wavelength reflects off the concave portion.
38. An apparatus as in claim 33, wherein  
the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror has a flat portion which continuously changes to a concave portion in correspondence with an increase in the wavelength of the output light above a specific wavelength so that output light at a shorter wavelength than the specific wavelength is incident on the flat portion and output light at a longer wavelength than the specific wavelength is incident on the concave portion.

39. An apparatus as in claim 33, wherein

the output light focused by the lens is incident on a different surface point on the mirror as the wavelength of the output light changes, and

the mirror has a convex portion which continuously changes to a flat portion in correspondence with an increase in the wavelength of the output light above a specific wavelength so that output light at a shorter wavelength than the specific wavelength is incident on the convex portion and output light at a longer wavelength than the specific wavelength is incident on the flat portion.

40. An apparatus as in claim 1, wherein the output light travelling from the VIPA generator to the lens does not overlap with the returned output light travelling from the lens to the VIPA generator.

41. An apparatus as in claim 8, wherein the output light travelling from the angular dispersive component to the lens does not overlap with the returned output light travelling from the lens to the angular dispersive component.

42. An apparatus as in claim 1, wherein the lens focuses light as seen from both a top view and a side view of the lens and has the same focal length in the top and side view of the lens.

43. An apparatus as in claim 8, wherein the lens focuses light as seen from both a top view and a side view of the lens and has the same focal length in the top and the side view of the lens.

44. An apparatus for receiving an input light and producing a spatially distinguishable output light, the apparatus comprising:

first and second surfaces separated from each other with air in between, the second surface having a reflectivity which allows a portion of light incident thereon to be transmitted therethrough, the first and second surfaces being positioned so that the input light is reflected a plurality of times between the first and second surfaces through the air to cause a plurality of lights to be transmitted through the second surface, the plurality of transmitted lights interfering with each other to produce the output light,

wherein the input light is at a respective wavelength within a continuous range of wavelengths and the output light is spatially distinguishable from an output light formed for an input light having any other wavelength within the continuous range of wavelengths.

45. An apparatus for receiving a wavelength division multiplexed light comprising at least two carriers, and producing a spatially distinguishable output light for each carrier, the apparatus comprising:

first and second surfaces separated from each other with air in between, the second surface having a reflectivity which allows a portion of light incident thereon to be transmitted therethrough, the first and second surfaces positioned so that the wavelength division multiplexed light is reflected a plurality of times between the first and second surfaces through the air to cause a plurality of lights to be transmitted through the second surface, the plurality of transmitted lights interfering with each other to produce a respective output light for each carrier of the wavelength division multiplexed light,

wherein each carrier is at a respective wavelength within a continuous range of wavelengths and the output light formed for a respective carrier is spatially distinguishable from an output light formed for a carrier having any other wavelength within the continuous range of wavelengths.

46. An apparatus comprising:

first and second surfaces separated from each other with air in between, the second surface having a reflectivity which causes a portion of light incident thereon to be transmitted therethrough, wherein

an input light at a respective wavelength is focused into a line, and

the first and second surfaces are positioned so that the input light radiates from the line to be reflected a plurality of times between the first and second



surfaces through the air and thereby cause a plurality of lights to be transmitted through the second surface, the plurality of transmitted lights interfering with each other to produce an output light which is spatially distinguishable from an output light produced for an input light at a different wavelength.

47. An apparatus comprising:

first and second surfaces separated from each other with air in between, the second surface having a reflectivity which causes a portion of light incident thereon to be transmitted therethrough, wherein

an input light at a respective wavelength is focused into a line, and  
the first and second surfaces are positioned so that the input light radiates from the line to be reflected a plurality of times between the first and second surfaces through the air and thereby cause a plurality of lights to be transmitted through the second surface, each transmitted light interfering with each of the other transmitted lights to produce an output light which is spatially distinguishable from an output light produced for an input light at a different wavelength.

48. An apparatus receiving an input light having a respective wavelength within a continuous range of wavelengths, the apparatus comprising:

first and second surfaces spaced apart from each other with air in between; and  
means for causing multiple reflection of the input light between the first and second surfaces through the air to produce self-interference that forms an output light, wherein the

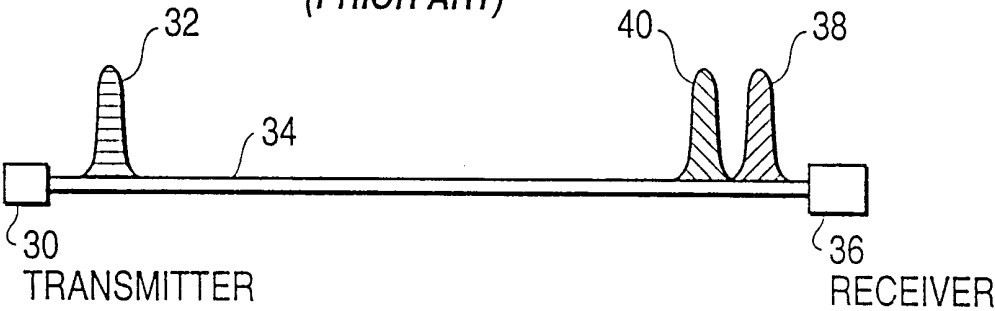
output light is spatially distinguishable from an output light formed for an input light having any other wavelength within the continuous range of wavelengths.

49. An apparatus receiving an input light at a respective wavelength and focused into a line, the apparatus comprising:

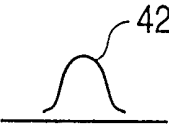
first and second surfaces spaced apart from each other with air in between; and

means for causing the input light to radiate from the line to be reflected a plurality of times between the first and second surfaces through the air and thereby cause a plurality of lights to be transmitted through the second surface, and for causing the transmitted lights to interfere with each other to produce an output light which is spatially distinguishable from an output light produced for an input light at a different wavelength.

**FIG. 1(A)**  
(PRIOR ART)



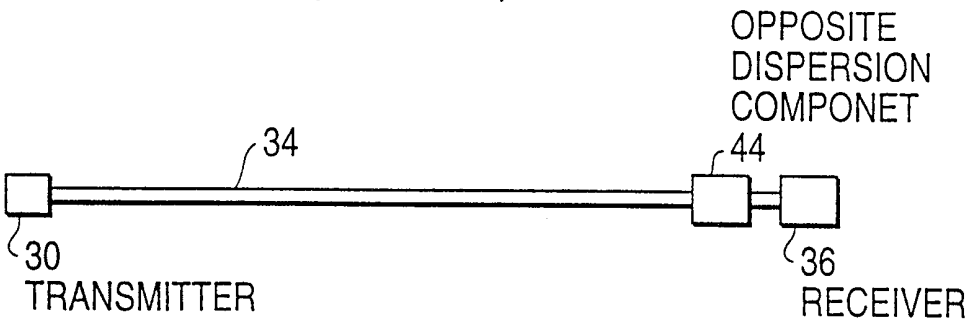
**FIG. 1(B)**



**FIG. 1(C)**

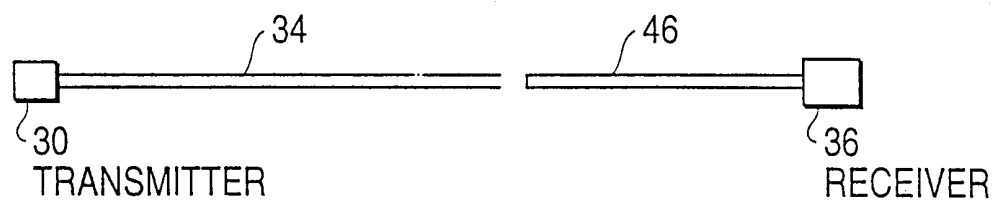


**FIG. 2**  
(PRIOR ART)

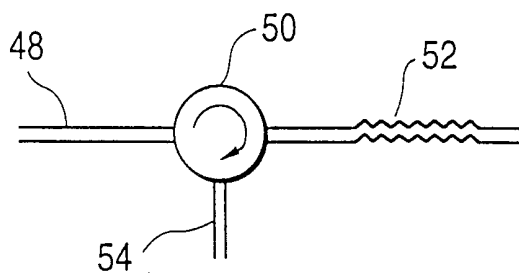


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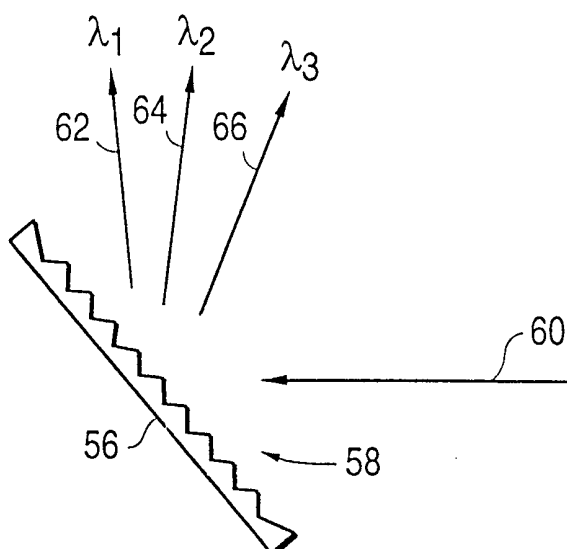
**FIG. 3**  
(PRIOR ART)



**FIG. 4**  
(PRIOR ART)

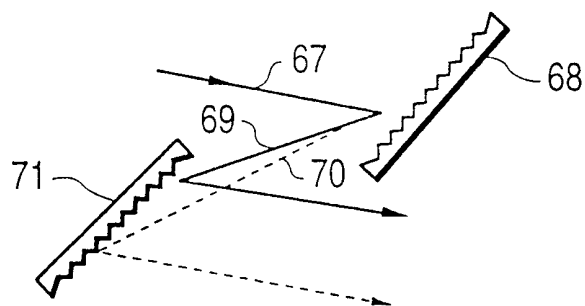


**FIG. 5**  
PRIOR ART

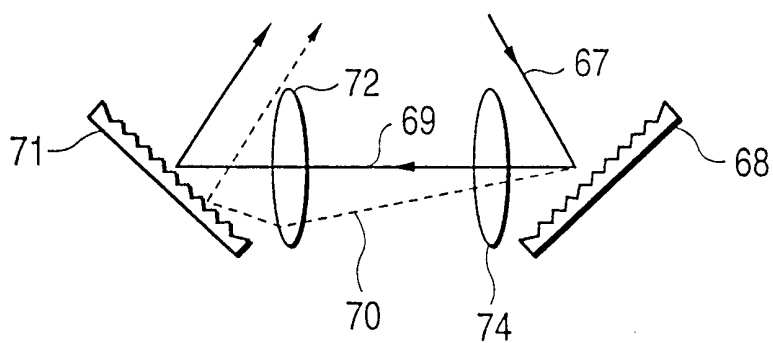


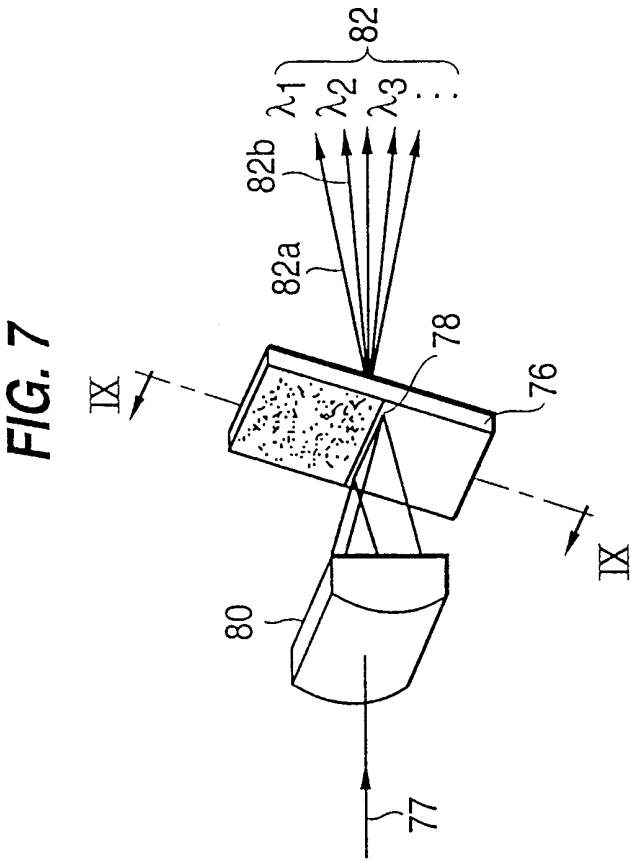
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**FIG. 6(A)**  
(PRIOR ART)



**FIG. 6(B)**  
(PRIOR ART)





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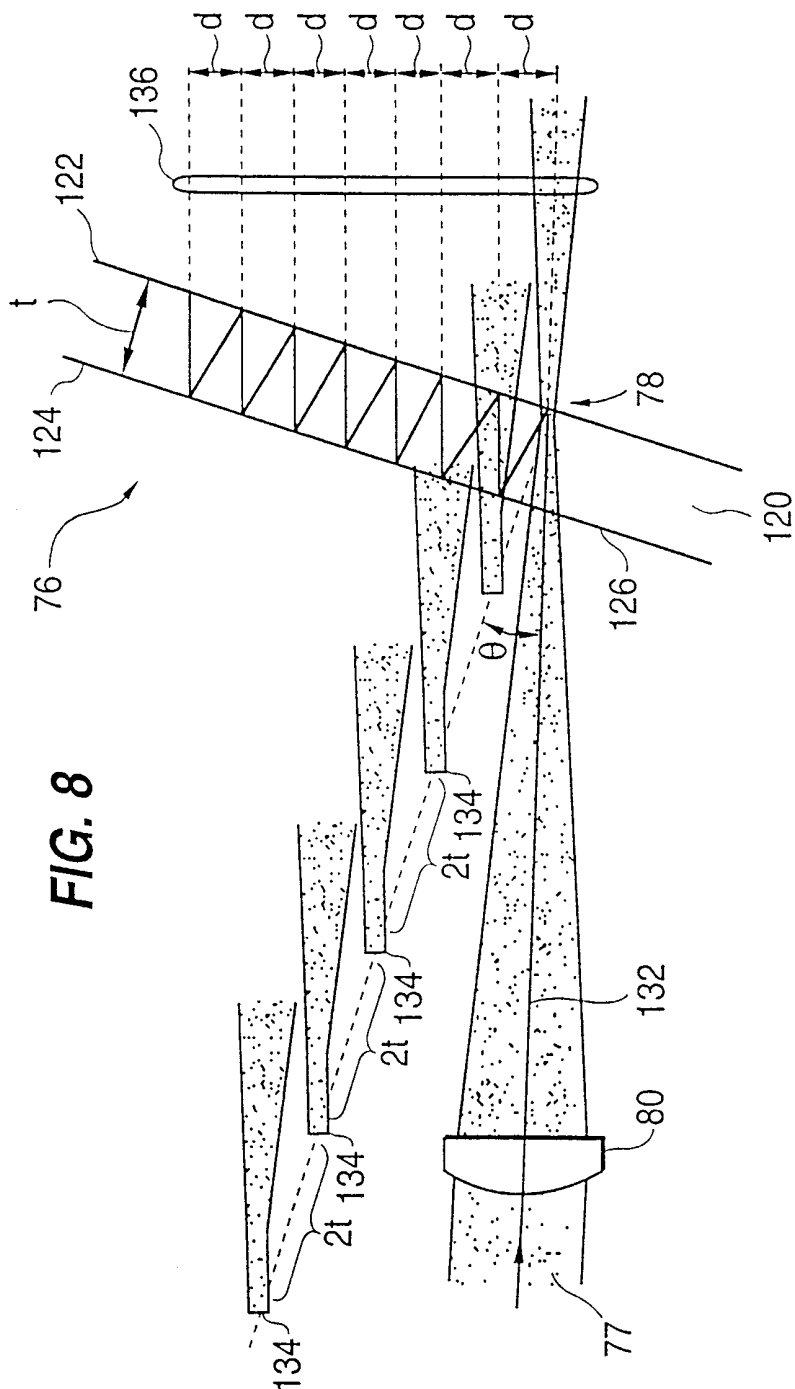
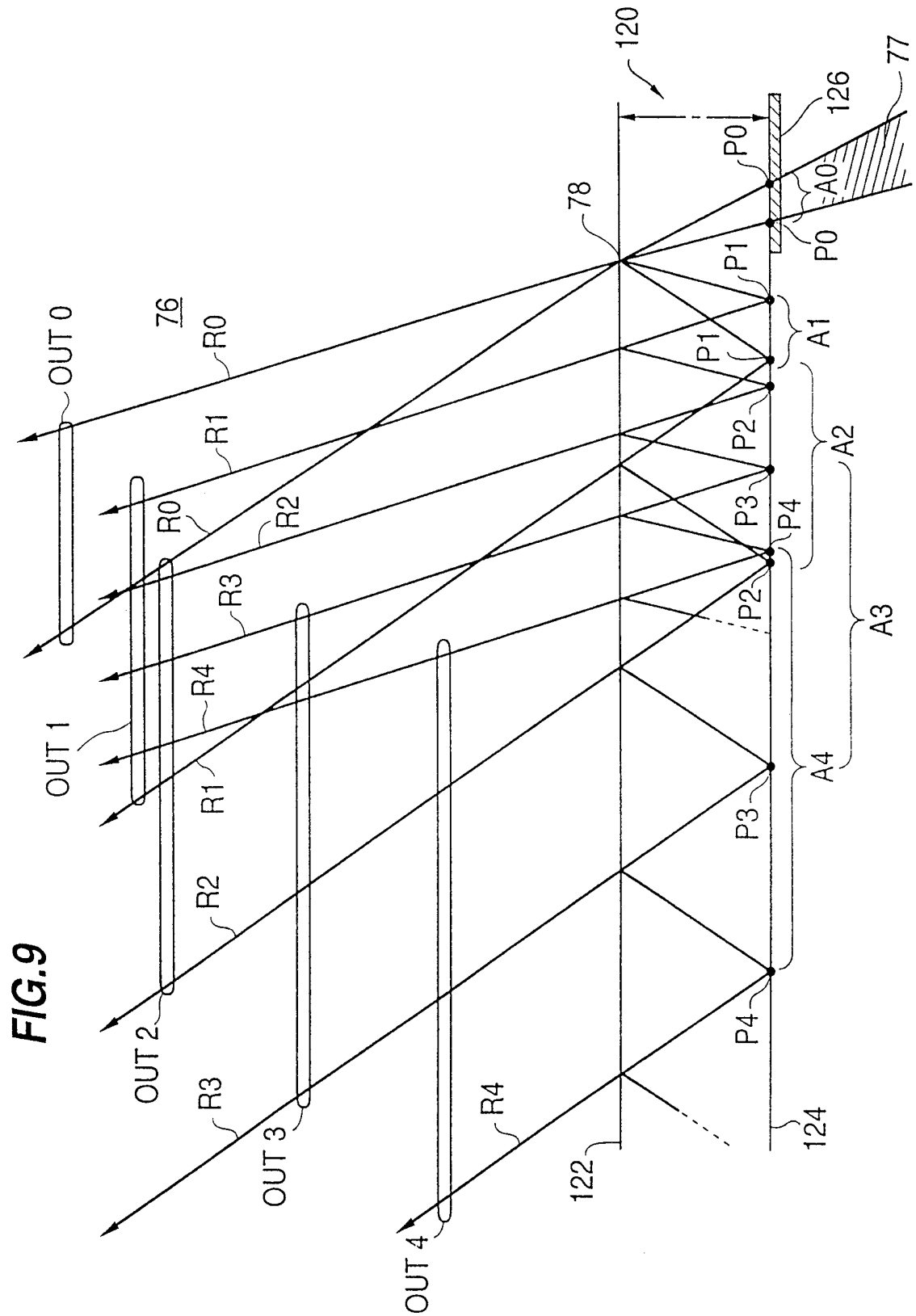
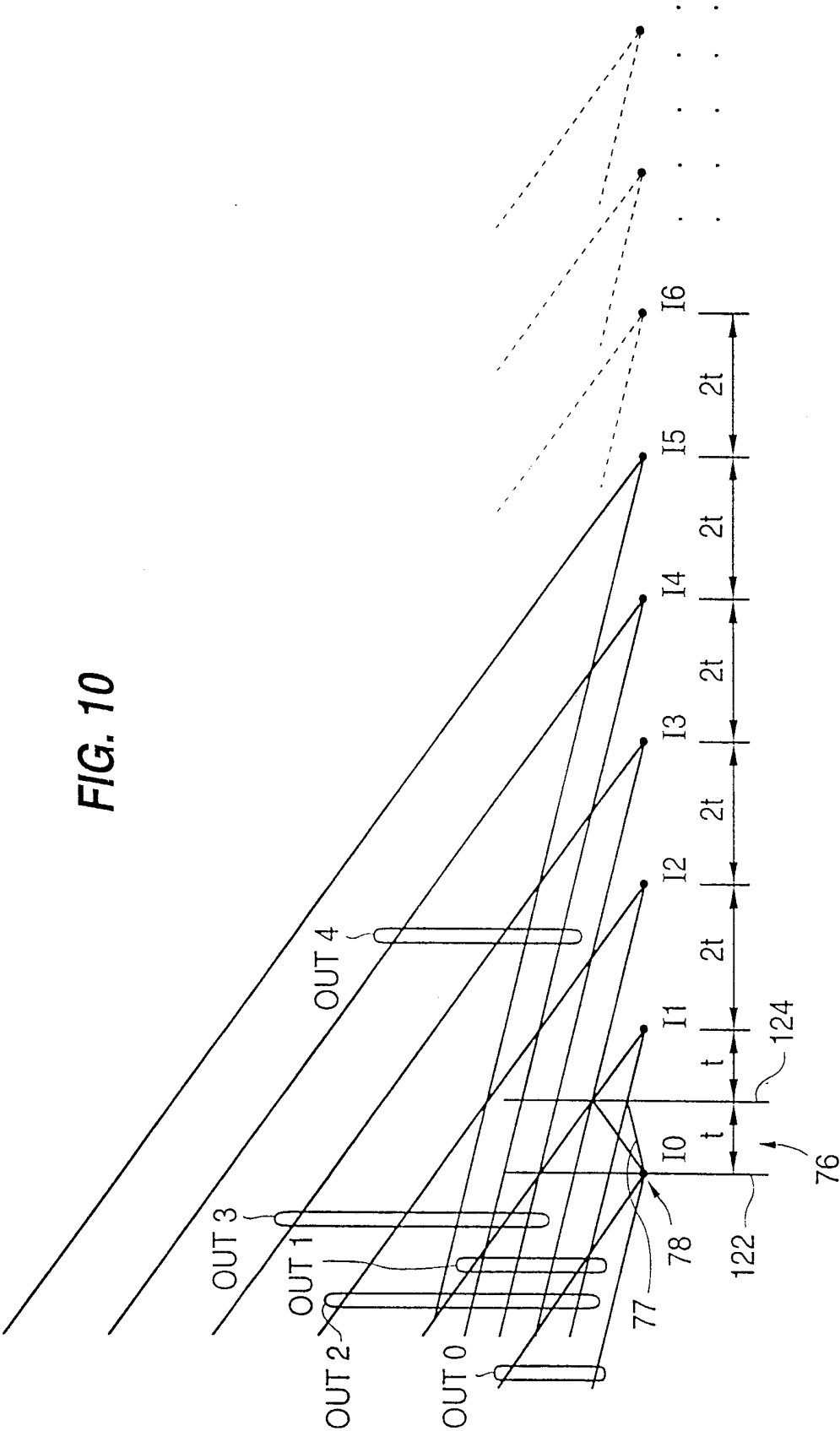


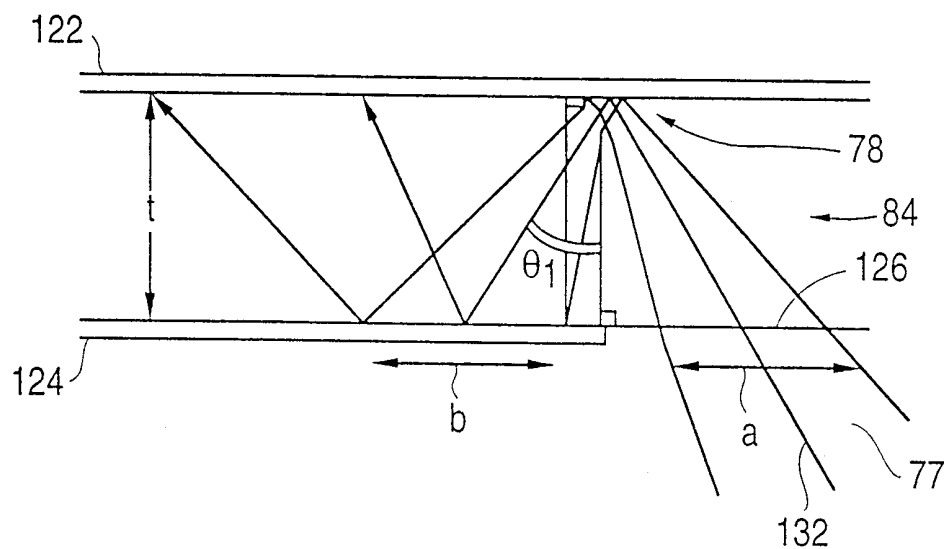
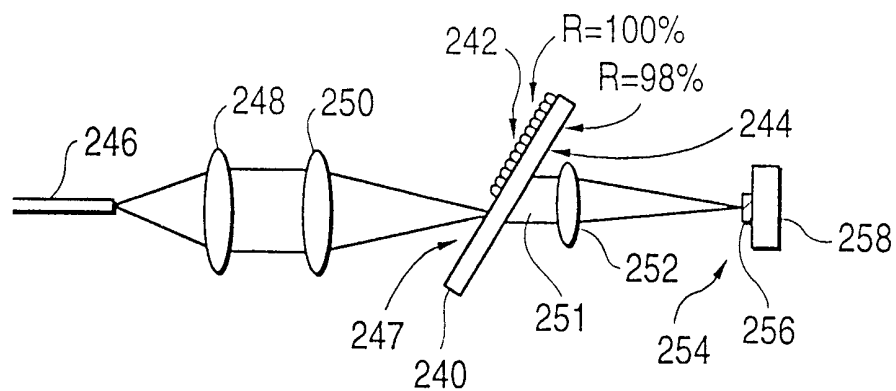
FIG. 8



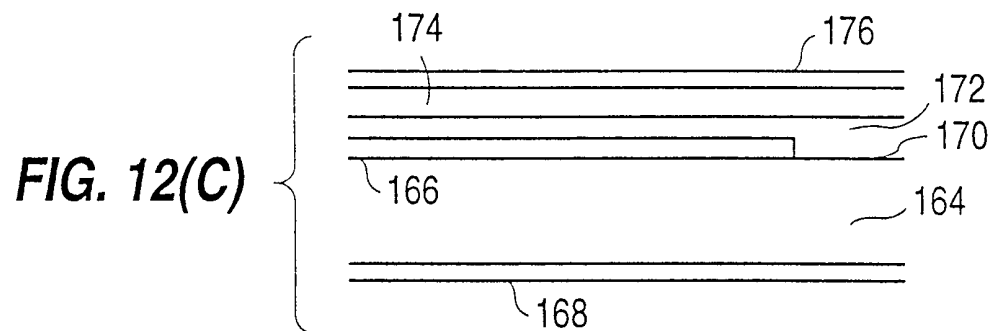
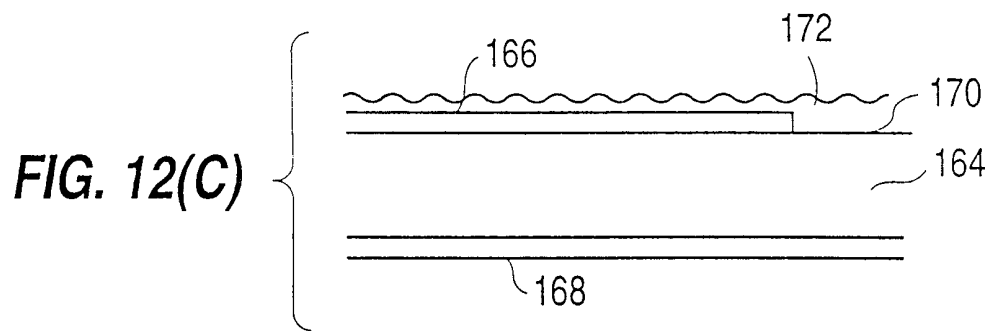
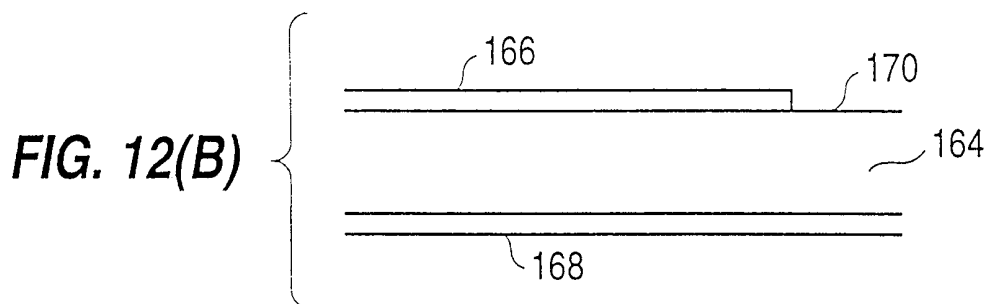
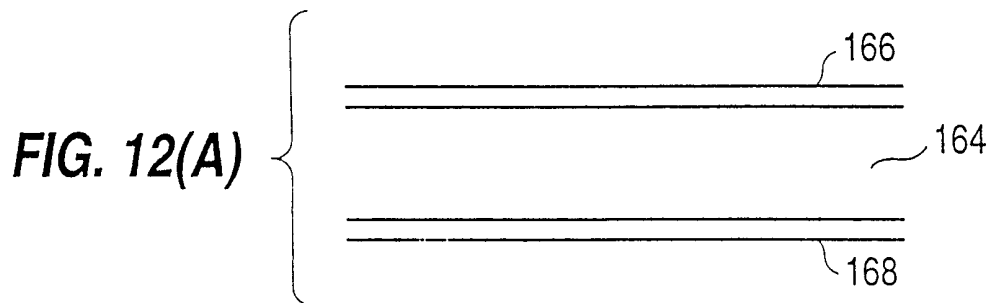




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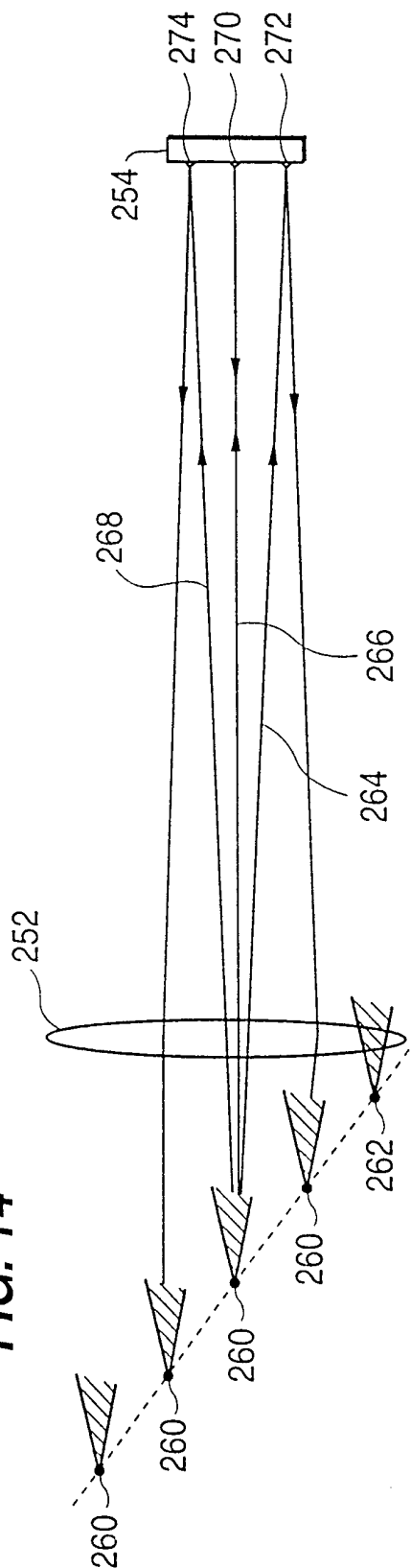
**FIG. 11****FIG. 13**

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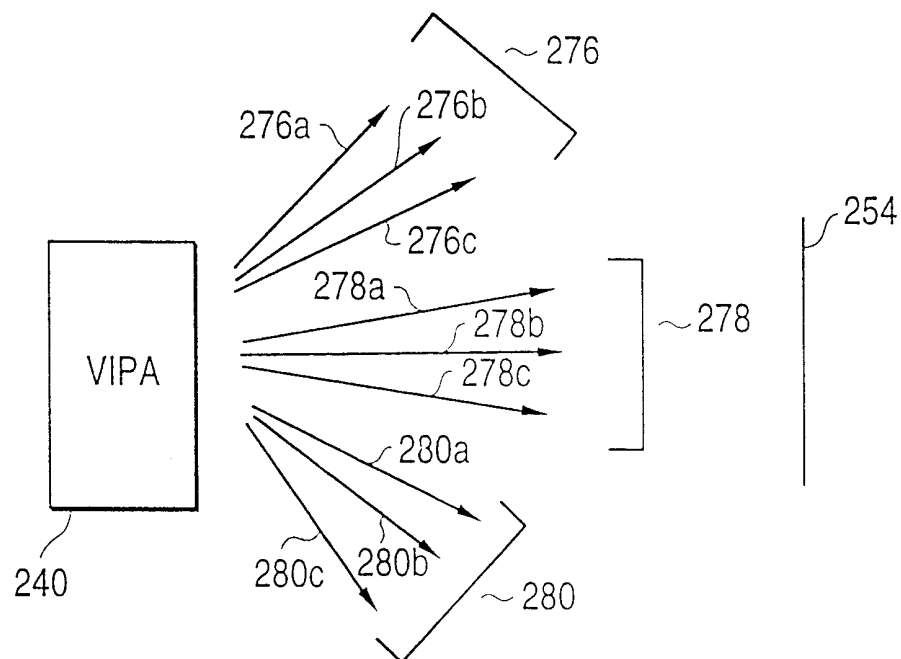
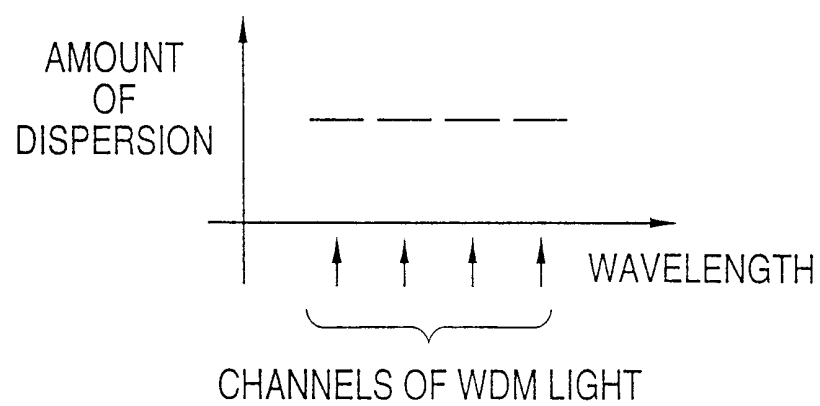


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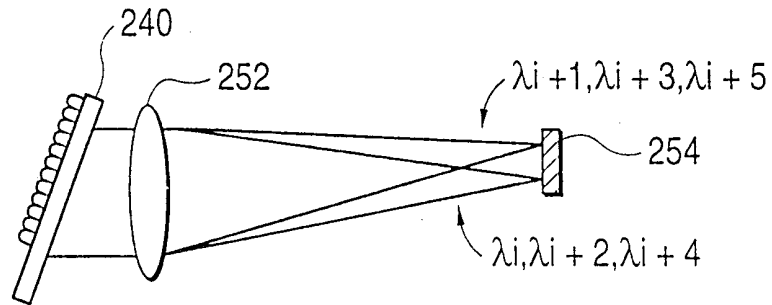
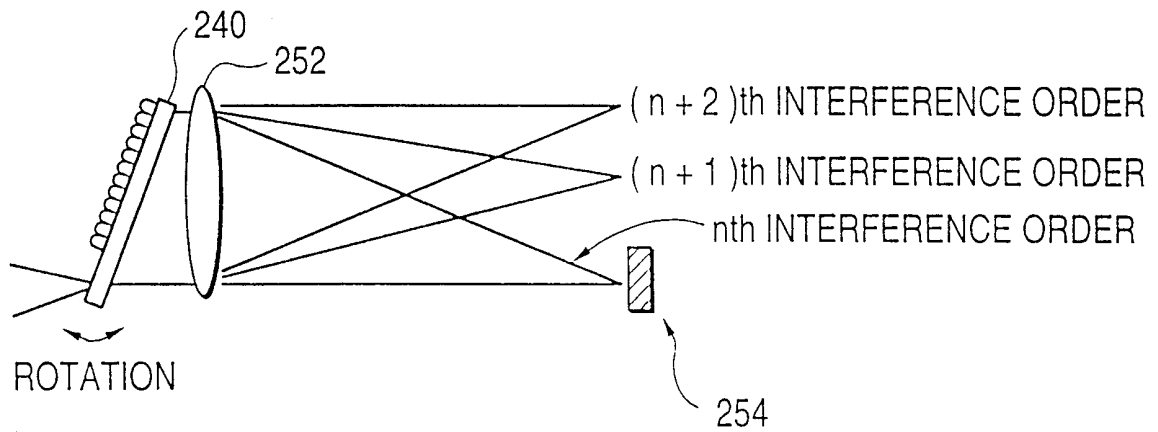
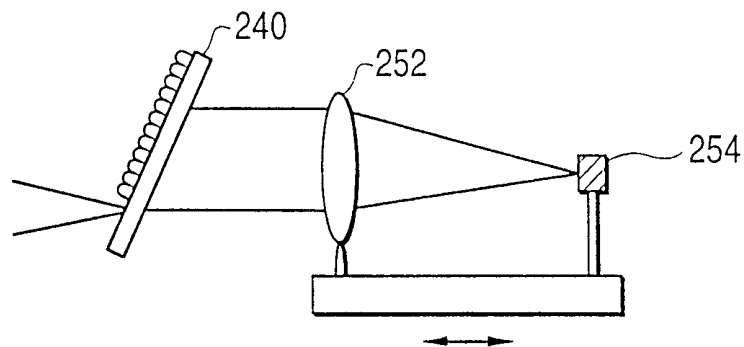
FIG. 14



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**FIG. 15****FIG. 16**

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**FIG. 17****FIG. 18****FIG. 19**

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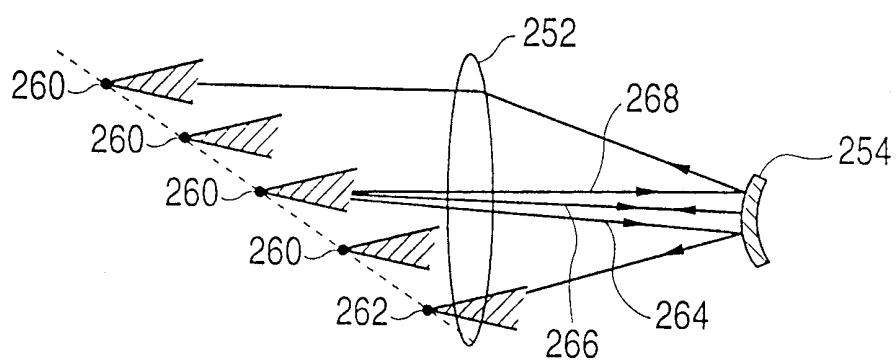
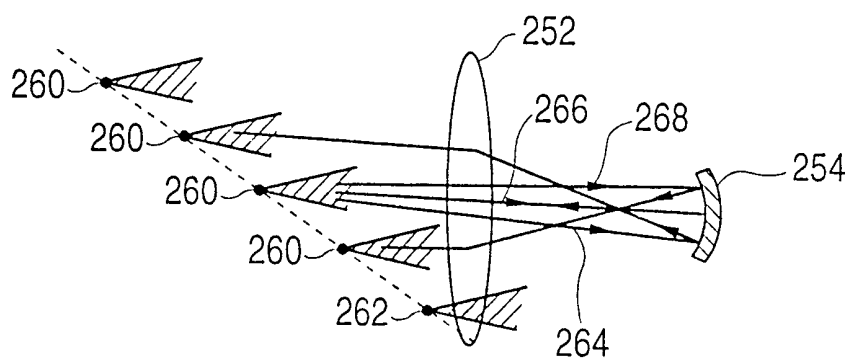
**FIG. 20(A)****FIG. 20(B)**

FIG. 21

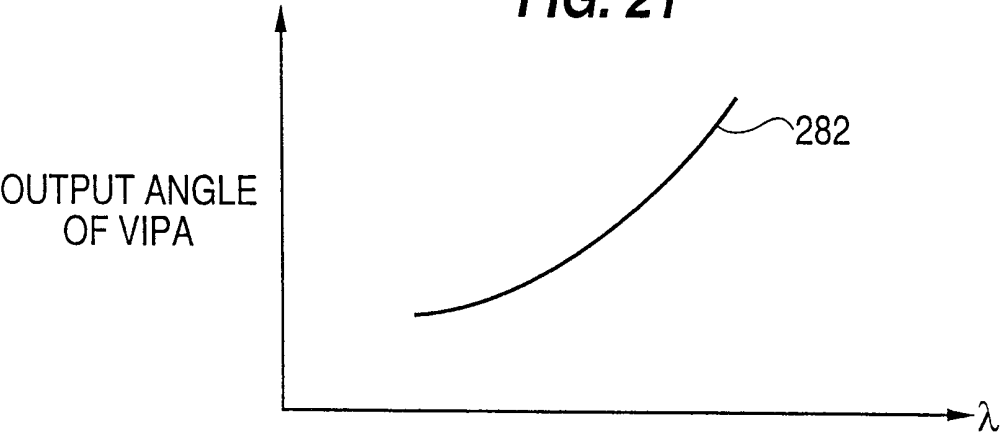


FIG. 22

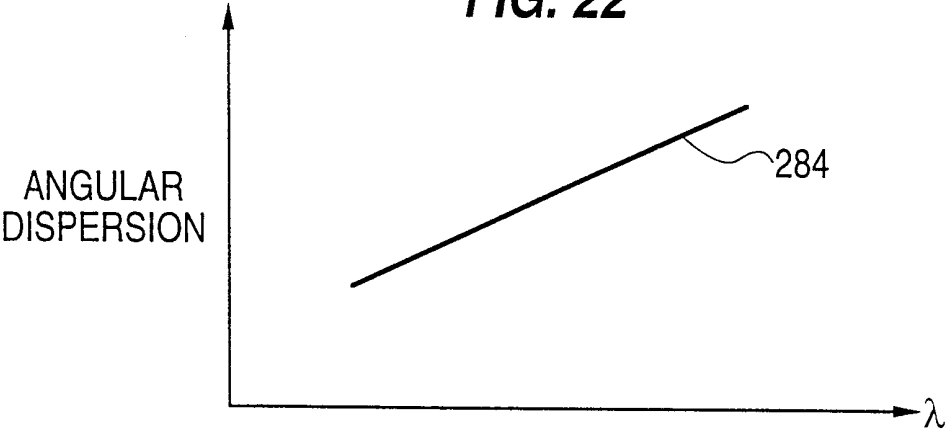
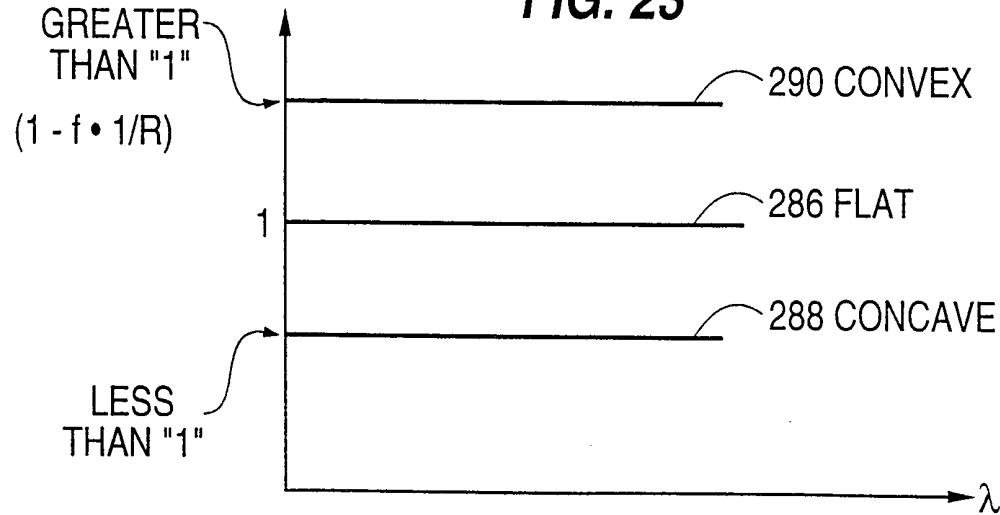
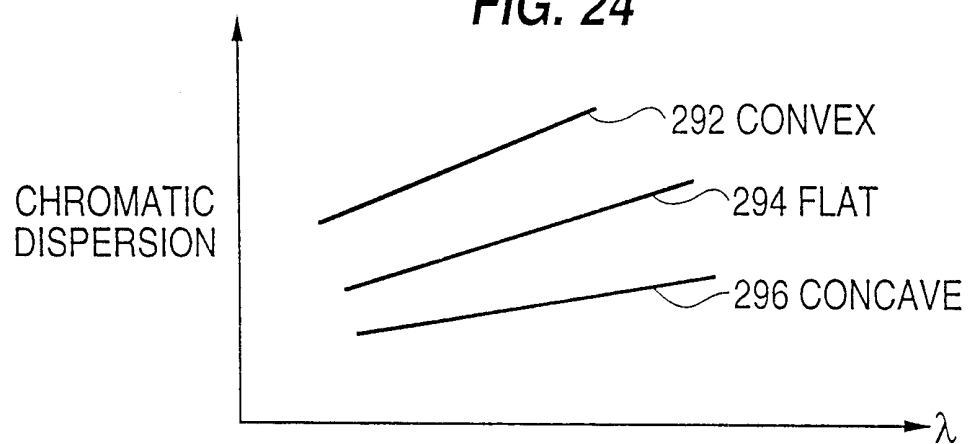
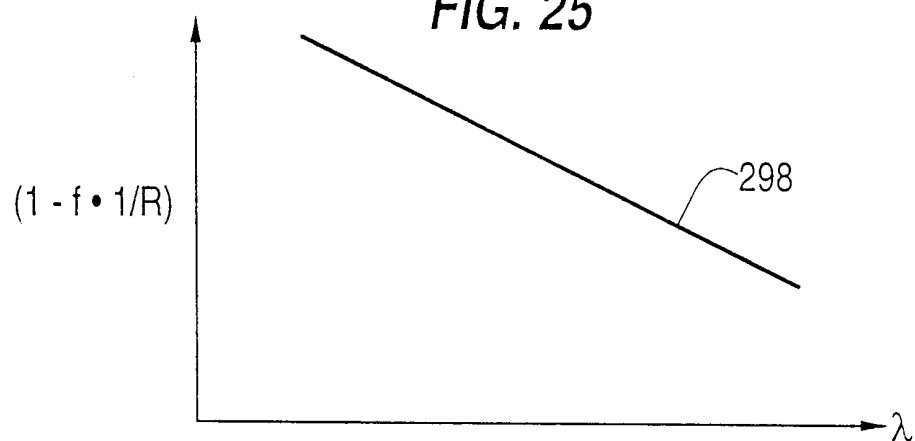
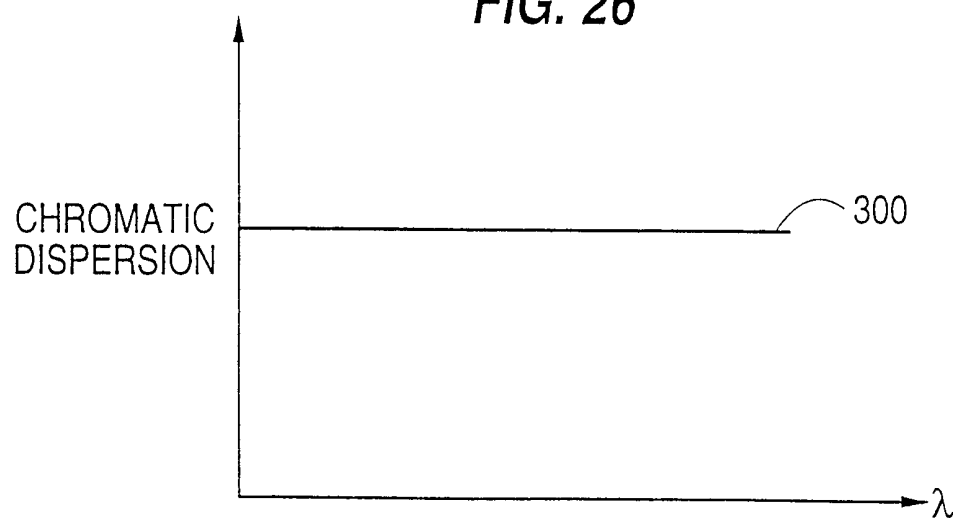


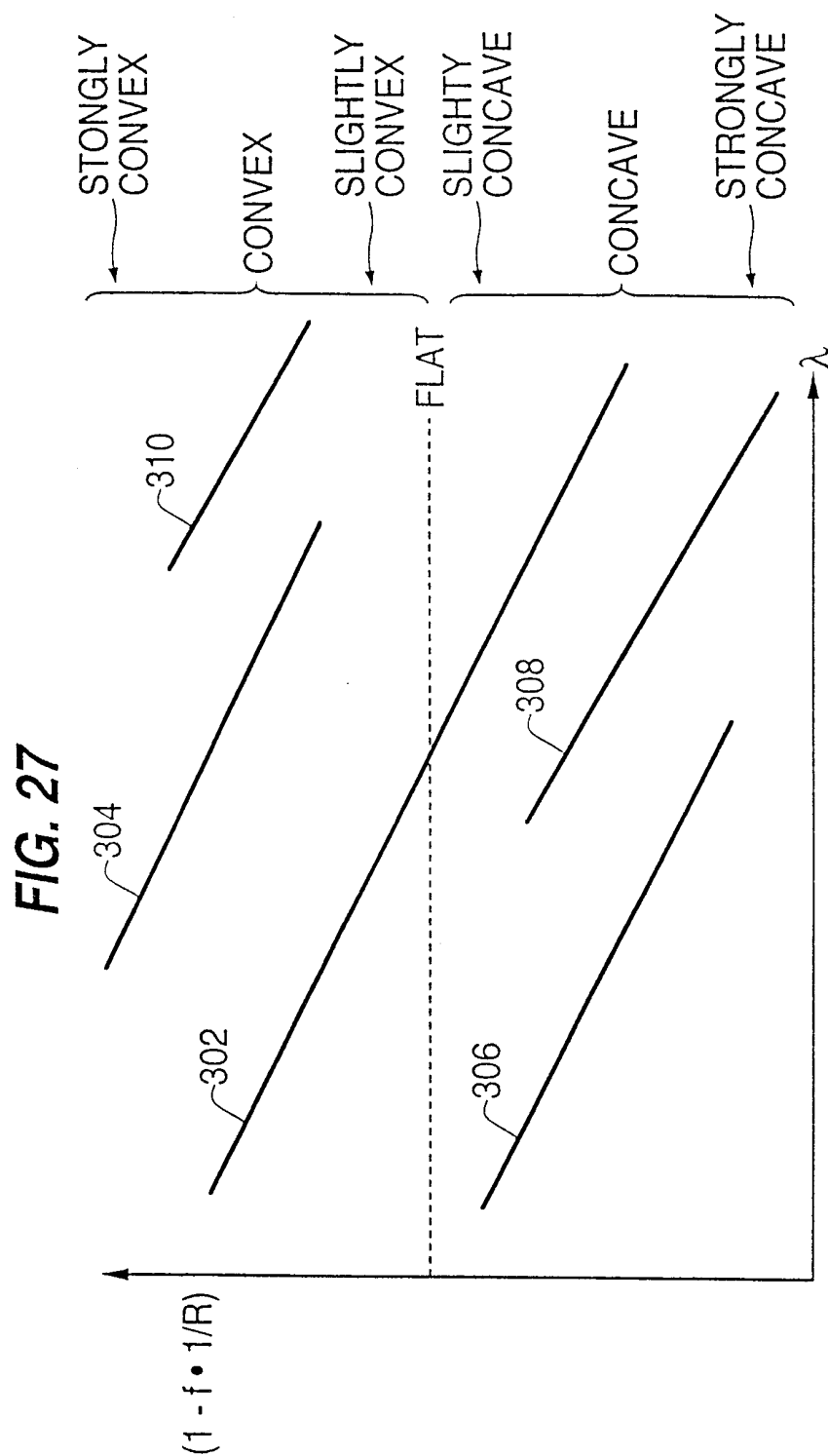
FIG. 23



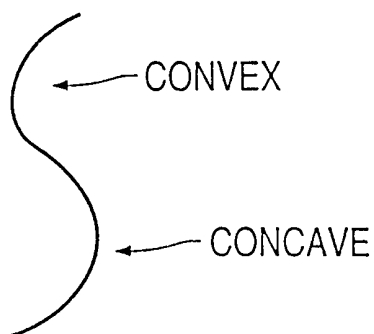


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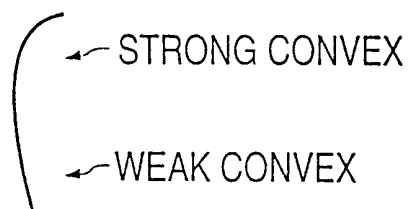
**FIG. 24****FIG. 25****FIG. 26**



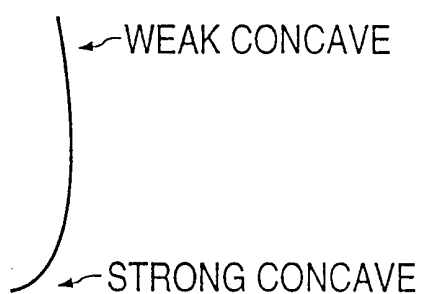
**FIG. 28(A)**



**FIG. 28(B)**



**FIG. 28(C)**



**FIG. 28(D)**



**FIG. 28(E)**

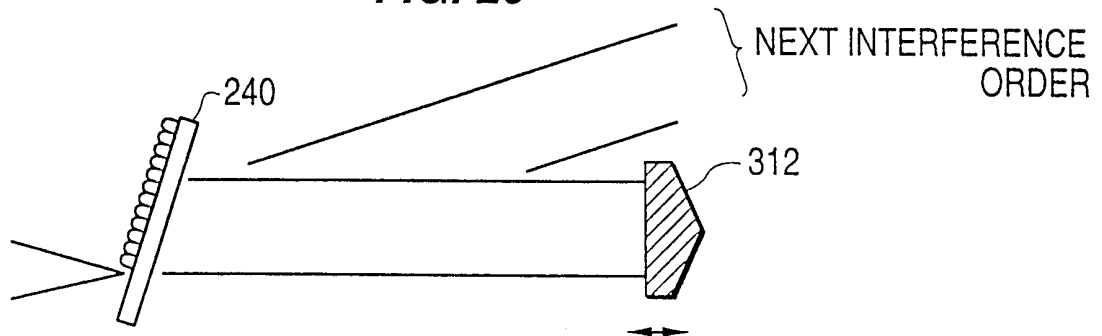


**FIG. 28(F)**

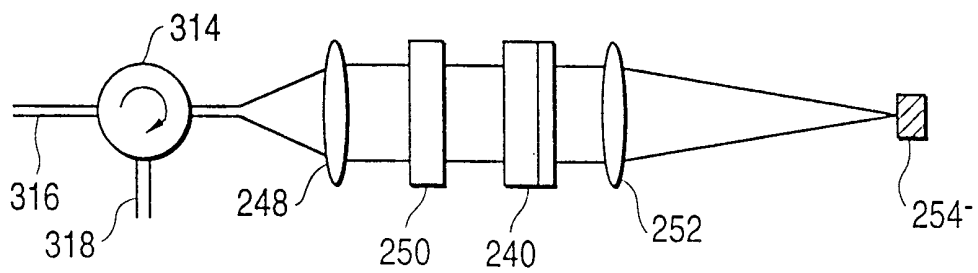


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**FIG. 29**



**FIG. 30**



**FIG. 31**

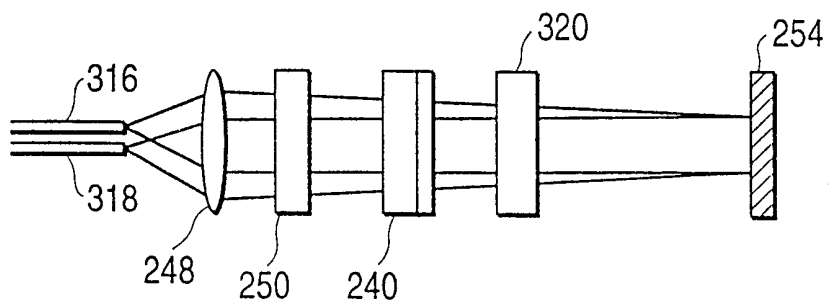
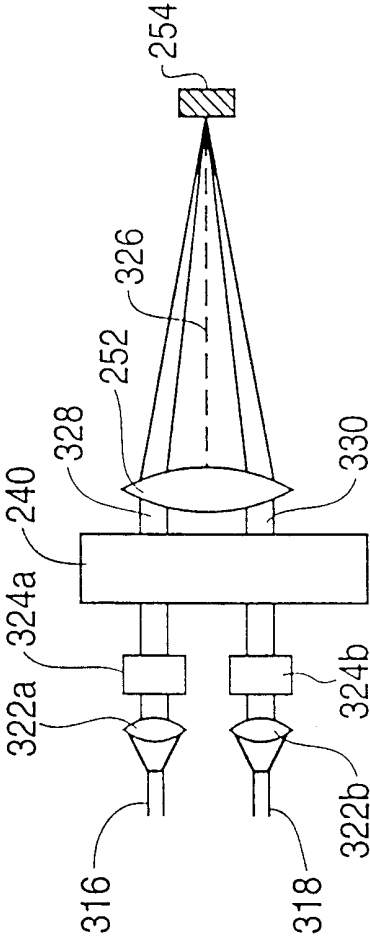
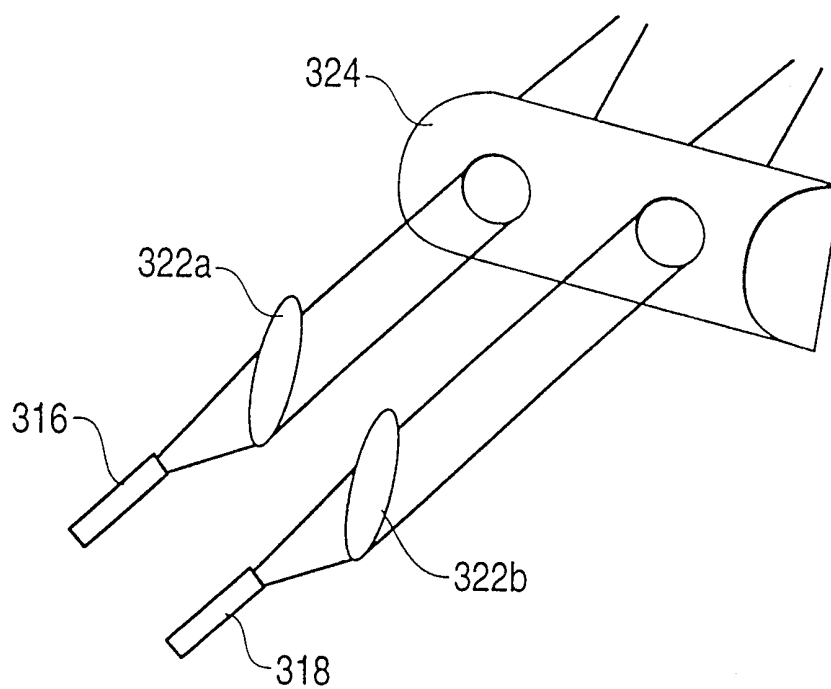


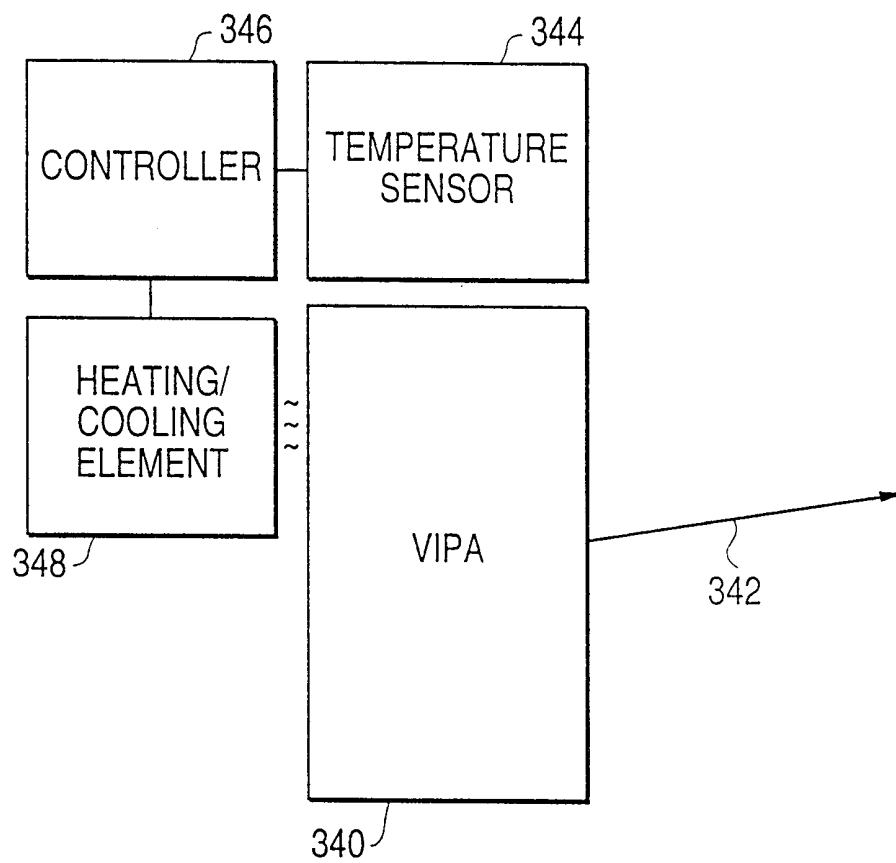
FIG. 32



**FIG. 33**



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**FIG. 34**

## INTERNATIONAL SEARCH REPORT

 International application No.  
PCT/US98/00433

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G02B 27/00, 5/04, 6/26

US CL : 359/577, 615, 385/27

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/577, 615, 114, 127, 578, 579, 839, 856, 857; 385/27, 15, 39; 372/25; 356/846, 352

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched  
(NONE)

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

APS

search terms: virtual, image, phased, array, dispersion, compensation

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3,832,030 A (GLOGE) 27 August 1974 (27/08/74), see entire document, especially column 3, lines 19-59; Figure 2.	1-27
A	US 4,655,547 A (HERITAGE, ET AL) 07 April 1987 (07/04/87), see entire document, especially column 5, lines 13-62; Figure 2.	4,5,7,13
A	US 4,820,019 A (YOSHIDA, ET AL) 11 April 1989 (11/04/89), see entire document; Figure 1.	1
A	AU 26,669 A (W. DOUDEN) 12 May 1930 (12/05/30), see entire document, especially Figures 9 & 10.	1



Further documents are listed in the continuation of Box C.



See patent family annex.

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

Date of the actual completion of the international search

23 APRIL 1998

Date of mailing of the international search report

09 JUL 1998

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Authorized officer

JOHN JUBA

Telephone No. (703) 308-4812



## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US98/00433

## C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,309,456 A (HORTON) 03 May 1994 (03/05/94), see column 3, line 28 - column 4, line 21; Figure 4.	1