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(54) **Filters**

(57) The present invention relates to filters, and is more particularly concerned with apodising filters.

As shown, a spatial discriminator 100 comprises an antenna array 102 consisting a plurality of antenna elements 102a, 102b, 102c, 102d, 102e, 102f, 102g, 102h. The antenna array 102 is a phased antenna array and each antenna element 102a, 102b, 102c, 102d, 102e, 102f, 102g, 102h has a fixed phase difference relative to each other antenna element. The antenna array 102 is connected to an array 104 of apodising filters. Each antenna element 102a, 102b, 102c, 102d, 102e, 102f, 102g, 102h is connected to a respective apodising filter element 104a, 104b, 104c, 104d, 104e, 104f, 104g, 104h.

The apodising may be carried out in the microwave domain or, alternatively, in the optical domain if the signals from the antenna array are converted from electrical signals to optical signals. Advantageously, if the apodising is carried out in the optical domain, commercial off the shelf components can be used in the array 104 of apodising filters.

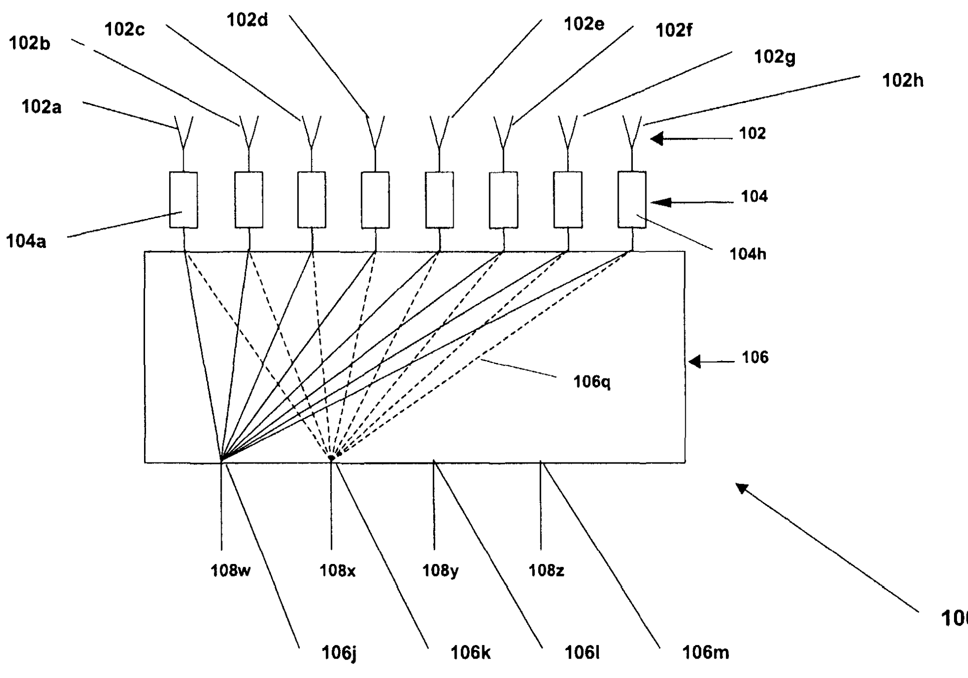

Fig. 1

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Description

[0001] The present invention relates to filters, and is more particularly concerned with apodising filters.

[0002] Apodisation is often used in the optical domain to modify transmission properties of an aperture to suppress unwanted optical aberrations or effects. However, apodisation can also be applied to other regions within the electromagnetic spectrum, for example, the microwave frequency range.

[0003] One application of apodisation at microwave frequencies is in phased antenna arrays used in spatial discriminator systems for determining angles of arrival of incoming signals.

[0004] In a phased antenna array, a beam is generated by maintaining a fixed phase difference between elements of the antenna array. The shape of the beam which is generated from the antenna array is dependent on:-

- the size of the array aperture
- the number of elements and their placement in the array
- the operating frequency of the array
- the excitation of each element (that is, the amplitude and phase applied to each element)
- the immersed element pattern
- the scattering from the array in the environment in which the antenna array is located

[0005] Where the antenna array comprises closely spaced elements, it behaves as if it is a continuous aperture. The pattern beamwidth is inversely proportional to the frequency. This means that as the frequency increases, the pattern beamwidth becomes narrower. This is undesirable for wide bandwidth spatial discriminator systems for determining the angle of arrival of an incoming signal by examining the relative beam output levels.

[0006] It is therefore an object of the present invention to provide a filter arrangement that improves the effectiveness of such wide bandwidth spatial discriminators.

[0007] In accordance with one aspect of the present invention, there is provided a method of controlling beam shape in a phased antenna array comprising the steps of:-

a) receiving signals at an antenna array;

b) apodising the received signals to taper the aperture distribution of the antenna array; and

c) processing the apodised signals.

[0008] The apodising may be carried out in the microwave domain or, altematively, in the optical domain if the signals from the antenna array are converted from electrical signals to optical signals.

[0009] In accordance with a second aspect of the present invention, there is provided a method of controlling beam shape in a phased array antenna comprising the steps of:

a) receiving a signal in a first frequency range at an antenna array;

b) imposing the signal onto a carrier signal, thereby forming a modulated carrier signal;

c) applying an apodising filter to the modulated carrier signal such that the beam shape is substantially constant throughout the first frequency range; and

d) processing the signal.

[0010] In accordance with a third aspect of the present invention, there is provided a filter arrangement including at least one apodising filter that provides a frequency-dependent taper on an aperture distribution.

[0011] In accordance with a fourth aspect of the present invention, there is provided a filter arrangement for controlling beam shape in a phased array antenna, the phased array antenna comprising a number of antenna elements to receive a signal in a first frequency range, and the apodising filter system comprises a number of channels, wherein one of the number of channels is associated with one of the number of antenna elements and comprises:

a frequency converter to impose the signal onto a carrier signal, thereby forming a modulated carrier signal; and
a filter element to apply a predetermined filter function to the modulated
carrier signal;

the number of channels thereby being arranged such that the beam shape is substantially constant across the first frequency range.

[0012] In accordance with a further aspect of the present invention, there is provided a spatial discriminator including a filter arrangement as described above.

[0013] For a better understanding of the present invention, reference will now be made, by way of example only, to the accompanying drawings in which:-

Figure 1 illustrates a wide bandwidth spatial discriminator in accordance with an embodiment of the present invention;

Figure 2 illustrates apodised intensity distributions at high and low frequencies;

Figure 3 is a schematic illustration of required filter characteristics;

Figure 4 illustrates the output from the Figure 1 spatial discriminator;

Figure 5 illustrates another embodiment of a wide bandwidth spatial discriminator in accordance with the present invention;

Figure 6 is similar to Figure 5 and illustrates the inclusion of optical patchcords;

Figure 7 is similar to Figure 6 and illustrates the use of electrical phase shifters;

Figure 8 is similar to Figure 6 and illustrates the use of optical delay trimming modules as altematives to electrical phase shifters;

Figure 9 illustrates a further embodiment of a wide bandwidth spatial discriminator in accordance with the present invention;

Figure 10 illustrates a profile of intensities on an optical carrier;

Figure 11 illustrates an intensity profile in which high frequency sidebands have been filtered out;

Figure 12 illustrates filter characteristics that provide the optimised profile of Figure 11;

Figure 13 illustrates an alternative method of combining the filter characteristics of Figure 12;

Figure 14 illustrates attenuation of the frequencies using the filter characteristics of Figure 10;

Figure 15 illustrates dispersion distributions for Figure 14;

Figure 16 is a schematic illustration of the use of an optical filter as a high-pass filter;

Figure 17 is a schematic representation of the use of an optical filter as a notch filter; and

Figure 18 is a flow diagram to illustrate a method of controlling optical filters in a wide bandwidth spatial discriminator.

[0014] When using monopulse techniques with a spatial discriminator, the error associated with the estimated angle of arrival is substantially smaller than an individual beamwidth. However, when there are multiple beams involved, the beam crossover levels, and hence beamwidths, must remain approximately constant over the bandwidth of interest. The pattern sidelobe levels must also remain sufficiently constant over the bandwidth. It is important to maintain the same beam shape across the bandwidth of a spatial discriminator so that the power needed to deconvolve the signal is much reduced. To accomplish this, frequency-dependent apodisation is used.

[0015] Conventionally, microwave frequency filters are used at the antenna array. This means that more components need to be provided in the region of the antenna array. However, when space is a premium, this provides many disadvantages. Furthermore, computer simulations show that the tolerance on the power for each element varies from 0.5 dB to 1 dB in order to maintain the beam shape. This is extremely difficult to achieve using conventional filtering techniques.

[0016] A spatial discriminator 100 comprises an antenna system as shown in Figure 1. The spatial discriminator 100 comprises an antenna array 102 consisting a plurality of antenna elements 102a, 102b, 102c, 102d, 102e, 102f, 102g, 102h. The antenna array 102 is a phased antenna array and each antenna element 102a, 102b, 102c, 102d, 102e, 102f, 102g, 102h has a fixed phase difference relative to each other antenna element.

[0017] The antenna array 102 is connected to an array 104 of apodising filters. Each antenna element 102a, 102b, 102c, 102d, 102e, 102f, 102g, 102h is connected to a respective apodising filter element 104a, 104b, 104c, 104d, 104e, 104f, 104g, 104h - only filter elements 104a and 104h are labelled for clarity. The array 104 of apodising filters is connected to a beamforming unit 106 having four output ports 106j, 106k, 1061, 106m. Each output port 106j, 106k, 106l, 106m provides an output signal 108w, 108x, 108y, 108z. Each output signal 108w, 108x, 108y, 108z comprises a combination of the signals output from the antenna elements 102a, 102b, 102c, 102d, 102e, 102f, 102g, 102h through the respective apodising filter elements 104a, 104b, 104c, 104d, 104e, 104f, 104g, 104h. This is indicated by solid lines 106p and dotted lines 106q connecting apodising filter elements 104a, 104b, 104c, 104d, 104e, 104f, 104g, 104h to respective output ports 106j, 106k. It will be appreciated that similar lines (not shown) are also present connecting the apodising filter elements 104a, 104b, 104c, 104d, 104e, 104f, 104g, 104h to output ports 106l, 106m.

[0018] The filter elements 104a, 104b, 104c, 104d, 104e, 104f, 104g, 104h are designed to apply a frequency-dependent amplitude across the aperture of the antenna array 102 as shown in Figure 2. Figure 2 illustrates the different intensity distributions according to the frequency of the received radiation. Here, the intensities from each of the antenna elements in the antenna array 102 (Figure 1), after filtering, are shown by dots 1202, 1204, 1206, 1208, 1210, 1212, 1214, 1216 and the distribution of these intensities across the array 102 is indicated by profiles 1220, 1230. Profile 1220 corresponds to a high frequency apodising intensity distribution and profile 1230 corresponds to a low frequency apodising intensity distribution. It will be noted that the distribution is flatter at low frequencies than at high frequencies. At high frequencies, the outer antenna elements are almost completely filtered out, so that the aperture is smaller. At low frequencies, the aperture is larger. The effective aperture, measured in terms of wavelengths, however, remains constant, and the beamshape is the same at both high and low frequencies.

[0019] The characteristics of the apodising filter elements 104a, 104b, 104c, 104d, 104e, 104f, 104g, 104h are therefore chosen so that the effective aperture size remains approximately constant irrespective of frequency. The required characteristics for some of the filters are shown in Figure 3. Filters 104c and 104f are required to have the characteristic 32 shown in Figure 3. Filters 104b and 104g are required to have the characteristic 34. Filters 104a and 104b are required to have the characteristic 36. It is apparent that the filter elements for the outer antenna elements require a stronger frequency-dependant tapering function than the inner filter elements. Furthermore, it is also apparent that a number of different filter functions are required.

[0020] Figure 4 illustrates the signals output from the spatial discriminator 100 shown in Figure 1. Signals 112w, 112x, 112y, 112z correspond to the signals formed by the beamforming unit 106 and output at ports 108w, 108x, 108y, 108z respectively.

[0021] Although only eight antenna elements 102a, 102b, 102c, 102d, 102e, 102f, 102g, 102h are shown, and hence eight input channels a, b, c, d, e, f, g, h, it will be appreciated that the antenna array 102 may comprise any number of elements. An embodiment having sixteen antenna elements is shown in Figure 5.

[0022] In Figure 5, a spatial discriminator 200 is shown that comprises an antenna array 202 and a filter array 204 of apodising filters. Here, there are sixteen antenna elements and hence sixteen channels. Note that the filter array 204 now comprises 16 filters, each of which may need a different frequency response in order to obtain a constant effective aperture size across a wide frequency band. A first amplifier array 206 is positioned between the antenna array 202 and the filter array 204, and a second amplifier array 208 is positioned after the filter array 204. It will be appreciated that, in each amplifier array 206, 208, an amplifier element is provided for each of the sixteen channels to amplify the signal at that stage.

[0023] Additionally, a modulator array 210 is located after, and connected to, the second amplifier array 208. The modulator array 210 comprises sixteen optical modulator elements for modulating the signals prior to their being processed by a beamforming module (not shown). In this embodiment, the signals received at antenna array 202 may be converted to optical signals prior to being processed in the beamforming module (not shown) of the spatial discriminator 200.

[0024] In Figure 6, a spatial discriminator 300 is shown that is similar to spatial discriminator 200. Components which are identical are referenced alike and no further description is given here. Spatial discriminator 300 includes an array 302 of selected optical patchcords between the modulator array and the beamforming unit (not shown). These patchcords are specific to each channel and help to compensate for phase differences introduced by differing electrical path lengths in each channel with respect to any other channel. These phase differences tend to vary linearly with frequency. Additionally, either variable electrical phase shifters (Figure 7) or optical time delay trimming modules (Figure 8) can be included to compensate for the phase differences.

[0025] In Figure 7, spatial discriminator 400 includes an array 402 of variable electrical phase shifters located between the second amplifier array 208 and the modulator array 210.

[0026] In Figure 8, spatial discriminator 500 includes an array 502 of optical delay trimming modules located adjacent the array 302 of optical patchcords and the beamforming unit (not shown).

[0027] In both Figures 7 and 8, components previously described with reference to Figures 5 and 6 have not been described further.

[0028] Figure 9 is similar to Figure 6 and whilst illustrating the array 302 of optical patchcords, does not illustrate either the variable electrical phase shifters shown in Figure 7 or the optical delay trimming modules shown in Figure 8, for clarity. As described previously with reference to Figure 5, there are sixteen channels in spatial discriminator 300. These channels are processed by a beamforming unit 600. However, the channels are grouped into two sets for processing - namely, set 1 comprising channels 1 to 8 and set 2 comprising channels 9 to 16. Set 1 is connected to a first beamforming element 602 which has four out-put ports 604, 606, 608, 610. (These output ports 604, 606, 608, 610 are equivalent to output ports 108w, 108x, 108y, 108z of Figure 1.) Similarly, set 2 is connected to a second beamforming element 612 which has four output ports 614, 616, 618, 620. The outputs from output ports 604, 606, 608, 610, 614, 616, 618, 620 are combined to provide output beams 630, 632, 634, 636 as shown. Beam 630 is formed from the outputs from ports 604 and 614; beam 632 is formed from the outputs from ports 606 and 616; beam 634 is formed from the outputs from ports 608 and 618; and beam 636 is formed from the outputs from ports 610 and 620.

[0029] It will be appreciated that any number of channels can be grouped together to form four output beams. For example, in a spatial discriminator having thirty-two channels, four beamforming elements are provided, each having eight input channels and four output ports. The outputs from each port having the same position (first, second, third, fourth) in the respective beamforming element are then combined to provide the four output beams from the beamforming unit.

[0030] In the above examples, the apodising filtering is carried out in the microwave domain, at the frequency of the incoming signals. Whilst such filtering results in the required constant effective aperture size, the microwave filters needed are expensive, bulky, and difficult to manufacture. A different component is needed for each characteristic (as shown, for example, in Figure 3) required. This adds complexity to the manufacturing process enhancing the possibility of manufacturing error, and is particularly disadvantageous where embodiments of the invention are to be incorporated into structures where there is little space, such as in the leading edge of an aircraft wing, or on periscope tops of submarines.

[0031] As an alternative to carrying out the apodising in the microwave domain, it can be carried out in the optical domain. In order to achieve this, an array microwave-to-optical converters is connected directly to the antenna array. The microwave-to-optical converter imposes microwave signals onto an optical carrier, thereby forming an optical signal. The optical carrier frequency can be provided by a laser, such as a distributed feedback (DFB) laser. Such lasers can be provided on small and robust semiconductor chips, and can therefore be conveniently placed in confined spaces, such as behind antenna elements on a wing leading edge. The carrier must be of a high fidelity: that is, the carrier linewidth must be narrow with respect to the modulation (microwave) frequency that is imposed on it. A typical semiconductor laser linewidth is less than 10MHz; over an hour, the frequency is typically stable to within 6MHz; and the absolute wavelength can be locked to one part in twenty million. These figures are to be compared with the laser carrier frequency that, for example, can be 200THz, and the microwave frequency of order of 20GHz. It is therefore apparent that a semiconductor distributed feed-back laser can conveniently provide the optical frequency carrier.

[0032] The optical signal output from the microwave-to-optical converters can then be fed, using optical fibres, to an array of optical filters that perform the apodising function. Optical fibres can efficiently transport the optical signal over larger distances than those over which microwave signals can be transported, and are readily available, robust components. By converting the signals to the optical domain before filtering, therefore, the filters can be placed wherever may be desired in the aircraft or other platform, and away from the possibly exposed situation of the antenna array itself. This also reduces the possibility of damage to the filters when the aircraft, or other platform, is in use.

[0033] In Figure 10, a profile 800 of light intensity output from the electrical-to-optical converter is shown. The intensity peak 802 corresponds to the optical carrier, and the sidebands 804 results from the modulation by the received microwave signals. The sidebands 804 are at optical frequencies, and it is therefore possible to shape them using optical filters. This shaping modifies the microwave signals that are carried by the optical signal, and can therefore be used to perform the apodising function described above without the need for expensive, complex and bulky microwave filters.

[0034] This is represented schematically in Figure 11, in which the profile 900 comprises an intensity peak 902 (the carrier signal) and sidebands 904 enclosed within an envelope 906 representing a filter function. It can be seen that the intensity peak 902 is effectively the same as the intensity peak 802 (Figure 10) of the non-filtered profile. However, the sidebands 904 have progressively decreasing peaks as shown. In order to provide the profile 900, optical filters (not shown) are required.

[0035] Two examples for optical filters that may be used are fibre Fabry-Perot filters (both single and multiple cavity) and thin film filters using multiple dielectric coatings. Fibre Fabry-Perot filters are similar to bulk etalons, in that they comprise a piece of single-mode fibre with highly reflecting ends, thus forming an electromagnetic cavity. The transmitted intensity of a single Fabry-Perot filter is given by:

$$I_t = I_o\{1 + B \sin^2(2\pi\ nd\nu\ /\ C)\}^{-1} \quad (1)$$

where

$$B = \frac{4R}{(1 - R)^2} \quad (2)$$

and R is the mirror reflectance, I_0 is the incident light intensity, *n* is the cavity refractive index, *d* is the distance between the mirrors, v is the frequency of the light and *c* the speed of light. Since the fibre is single-moded, fibre Fabry-Perot filters can exhibit very low loss as no light 'falls off' at the mirror edges. Thus a very high B can be obtained.

[0036] Fibre Fabry-Perot filters are also controllable and tuneable. The distance between the mirrors can be altered either by slightly heating or cooling the cavity, or by stretching it using piezoelectric drive. Furthermore, these filters are available as commercial off-the-shelf components, since they are used regularly in the telecoms industry.

[0037] To achieve the apodising function, the fibre Fabry-Perot filters must provide characteristics such as those shown by way of example in Figure 3. However, attempts to fit the Fabry-Perot function of equation (1) above show that the slope of the Fabry-Perot function is too small to provide the required characteristic. The maximum rate of intensity with frequency given by the Fabry-Perot function (equation (1) above) is an inverse square response, whereas inverse relationships to the eighth power are required to fit the filter characteristics needed for the outer antenna elements at high frequency (such as that referred to as 36 in Figure 3). Higher power inverse relationships may be required depending on the desired filter characteristic for a given application.

[0038] This problem can be solved by using two or more fibre Fabry-Perot filters combined in series. By combining Fabry-Perot filters of either the same or different characteristics, a much larger range of filter characteristics is obtainable.

[0039] This is illustrated in Figure 12. As shown, filter characteristics 1002, 1004 define a new filter characteristic 1006 when they are arranged to overlap. This new filter characteristic 1006 exhibits a flatter top, and steeper sides, than either of individual characteristics 1002 or 1004. It is therefore better suited to providing characteristics such as characteristic 36 shown in Figure 3. It can be used, for example, to provide characteristic 906 shown in Figure 11.

[0040] Figure 13 illustrates an alternative overlapping arrangement of filter characteristics 1002, 1004. In this arrangement, the filters used are centred on the same frequency, rather than separate frequencies as shown in Figure 12. This arrangement produces a narrower filter characteristic 1008.

[0041] Figure 14 illustrates an envelope 1102 that is defined by filter characteristics 1104, 1106. Filter characteristics 1104, 1106 correspond to filter characteristics 1002, 1004 (Figure 13), but they are further apart so that the envelope 1102 also includes a more significant attenuation of the low frequencies, as well as higher attenuation of the higher frequencies.

[0042] For each filter characteristic 1104, 1106, its dispersion characteristics 1114, 1116 is also shown in Figure 14. These dispersion characteristics can be summed as illustrated in Figure 15. Elements that have been described previously are referenced the same. The sum of the dispersion characteristics 1114, 1116 is referenced as profile 1118. In the region 1120 of profile 1118, the profile is substantially flat. Region 1120, as will readily be appreciated, corresponds to the frequency range in which the envelope 1102 of Figure 14 actively filters the incoming signals.

[0043] Whilst two filter characteristics are shown in Figures 13, 14 and 15, it will be appreciated that any number of filters can be used to define the desired or optimised profile for the particular application. Ideally, a filter characteristic is used for each channel of the spatial discriminator 100 shown in Figure 1. Naturally, the characteristics of the filters are chosen to define the desired or optimised profile.

[0044] Other filter characteristics may also be obtained using fibre Fabry-Perot filters. The above examples provide low-pass filtering characteristics. By offsetting the centre frequency of the filters (or of the filter combination) a high-pass filter can be obtained. This is shown in Figure 16, where the filter characteristic 1310 is offset from the optical carrier frequency 1302, such that the sidebands 1304 and 1306 on the high frequency side of the carrier are transmitted, whereas those on the low frequency side, such as sideband 1312, have much reduced intensity. Other components may also be used. A notch filter is shown schematically in Figure 17, in which carrier frequency 1402 and sideband 1406 are substantially unaffected by filter characteristic 1410, whereas the intensity of sideband 1404 is dramatically reduced. Such a characteristic is achieved using an optical absorber.

[0045] It is noted that the apodising function can be achieved with sufficient precision for use in a phased array antenna using combinations of only two Fabry-Perot filters. Whilst it is possible to use more Fabry-Perot filters to achieve more widely varying functions, it is advantageous to keep the numbers used low so as to minimise any potential losses.

[0046] Figure 18 is a flow diagram to illustrate a method of controlling the optical filters using optical wavelength lockers (OWL's) such as those available from the Santec Corporation. A portion of the output from each optical filter 1802, 1804 is fed to an OWL 1806, 1808. Each filter is provided with an OWL. The OWL then feeds back a control signal to the optical filter. As shown OWL 1806 feeds back control signal 1810 to filter 1802, and OWL 1808 feeds back control signal 1812 to filter 1804. Similarly, a locker 1820 takes a proportion of the laser signal and feeds back a control signal 1822 to laser 1824. The laser 1824 can be modulated with a microwave signal such that its output is the optical signal described above. It is to be appreciated that the method could be applied to all the embodiments using optical filters described above, and is not limited to embodiments in which only two filters are used.

[0047] The above embodiments are to be understood as illustrative examples of the invention. Further embodiments of the invention are envisaged. It is to be understood that any feature described in relation to any one embodiment may be used alone, or in combination with other features described, and may also be used in combination with one or more features of any other of the embodiments, or any combination of any other of the embodiments. Furthermore, equivalents and modifications not described above may also be employed without departing from the scope of the invention, which is defined in the accompanying claims.

Claims

1. A method of controlling beam shape in a phased antenna array comprising the steps of:-

(a) receiving signals at an antenna array;

(b) apodising the received signals to taper the aperture distribution of the antenna array; and

(c) processing the apodised signals.

2. A method of controlling beam shape in a phased array antenna comprising the steps of:

(a) receiving a signal in a first frequency range at an antenna array;

(b) imposing the signal onto a carrier signal, thereby forming a modulated carrier signal;

(c) applying an apodising filter to the modulated carrier signal such that the beam shape is substantially constant throughout the first frequency range; and

(d) processing the signal.

3. A method as claimed in claim 2, wherein the antenna array comprises a number of antenna elements, and the apodising filter comprises a number of fibre Fabry-Perot filters, and wherein each fibre Fabry-Perot filter is associated with one of the number of antenna elements.

4. A filter arrangement including at least one apodising filter that provides a frequency-dependent taper on an aperture distribution.

5. A filter arrangement for controlling beam shape in a phased array antenna, the phased array antenna comprising a number of antenna elements to receive a signal in a first frequency range, and the apodising filter system comprises a number of channels, wherein one of the number of channels is associated with one of the number of antenna elements and comprises:

a frequency converter to impose the signal onto a carrier signal, thereby forming a modulated carrier signal; and

a filter element to apply a predetermined filter function to the modulated carrier signal;

the number of channels thereby being arranged such that the beam shape is substantially constant across the first frequency range.

6. An arrangement as claimed in claim 5 wherein the carrier signal is an optical signal.

7. An arrangement as claimed in claim 5 or claim 6 wherein the filter element is a fibre Fabry-Perot filter.

8. An arrangement as claimed in claim 5 or claim 6 wherein the filter element is a thin film filter.

9. A spatial discriminator including a filter arrangement as claimed in any of claims 4 to 8.

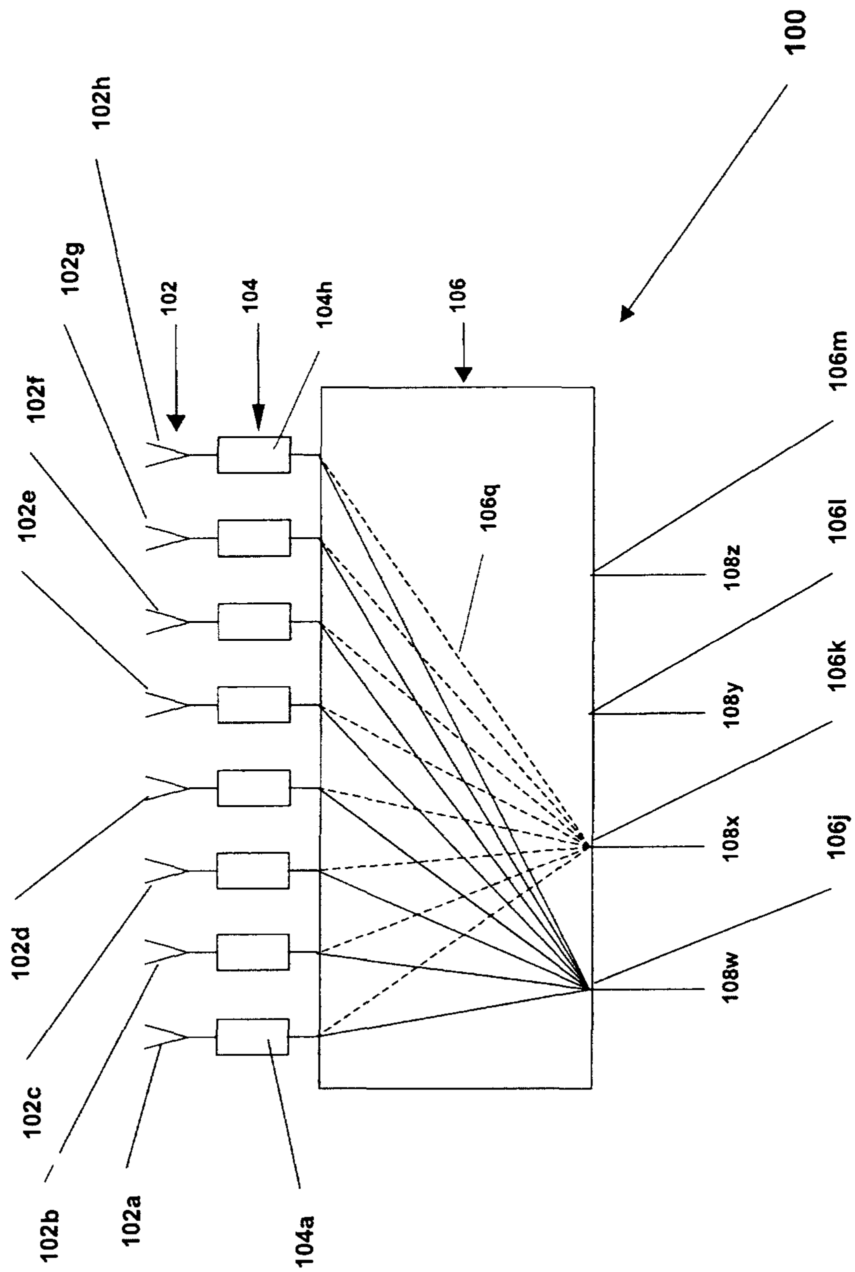
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Fig. 1

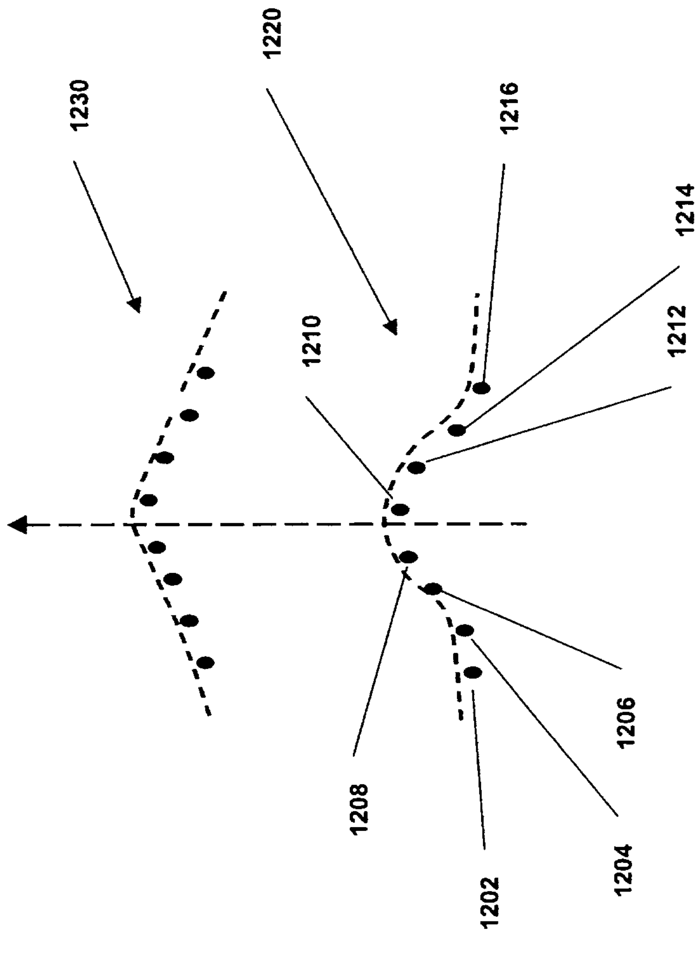

Fig. 2

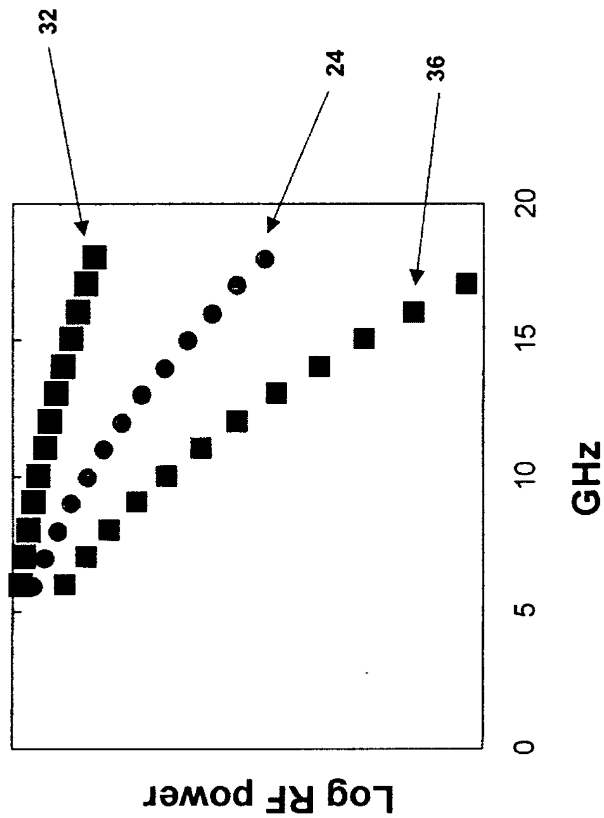

Fig. 3

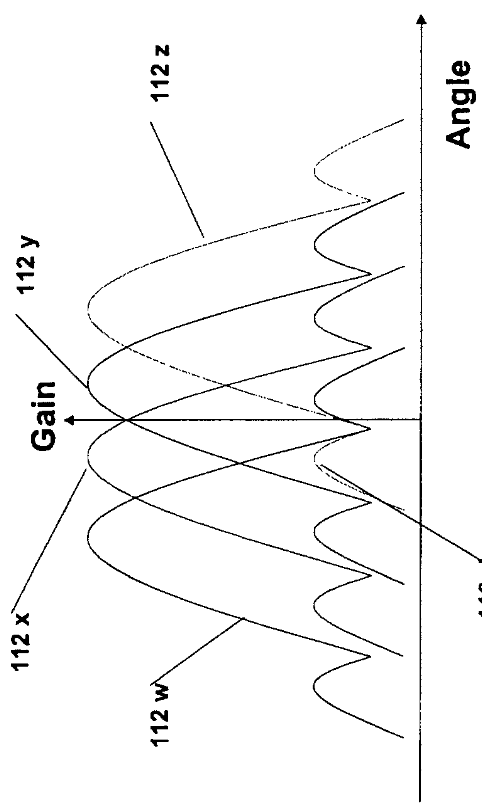

Fig. 4

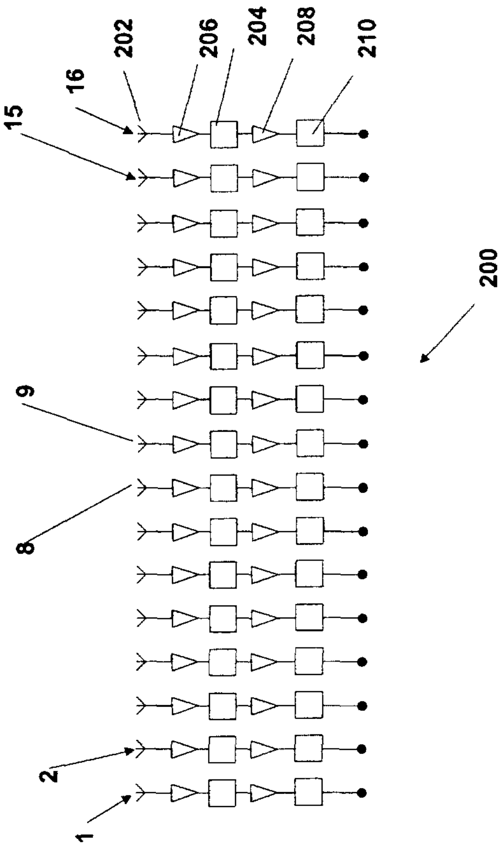

Fig. 5

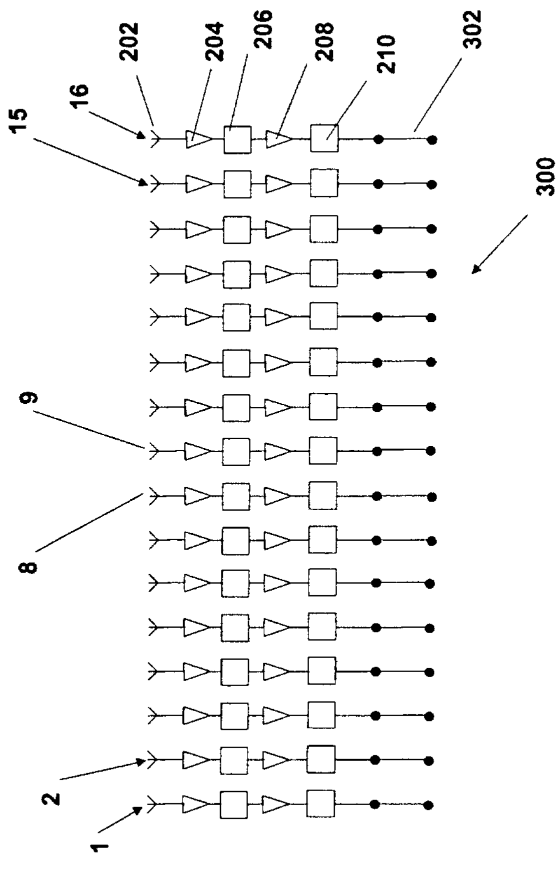

Fig. 6

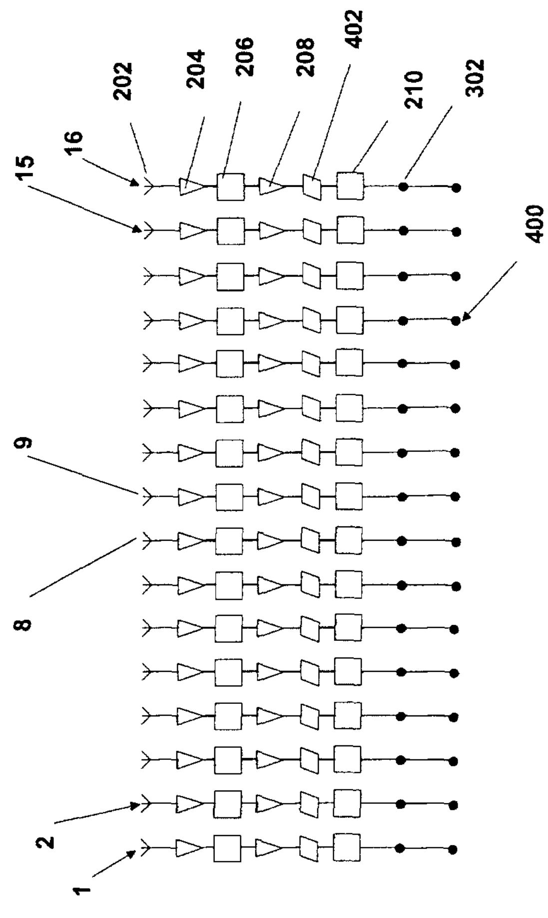

Fig. 7

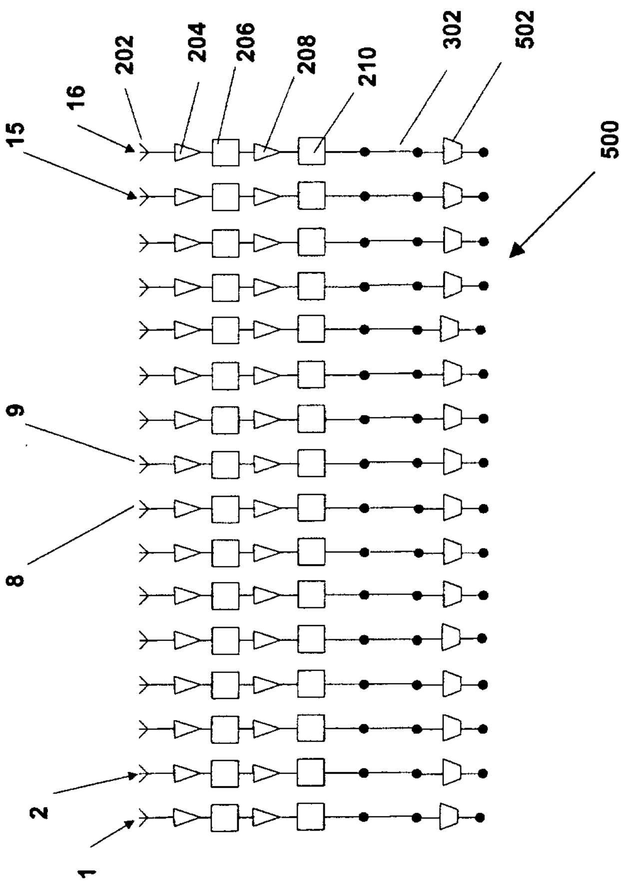

Fig. 8

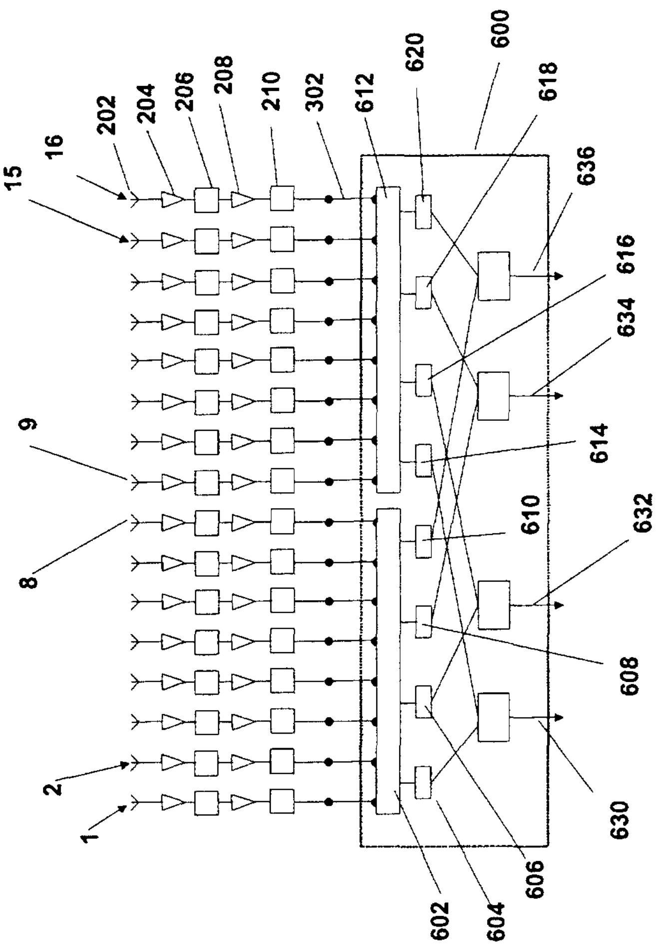
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Fig. 9

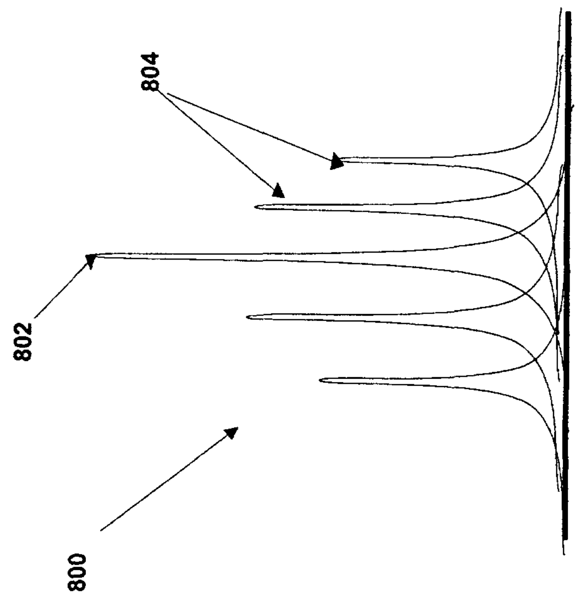


Fig. 10

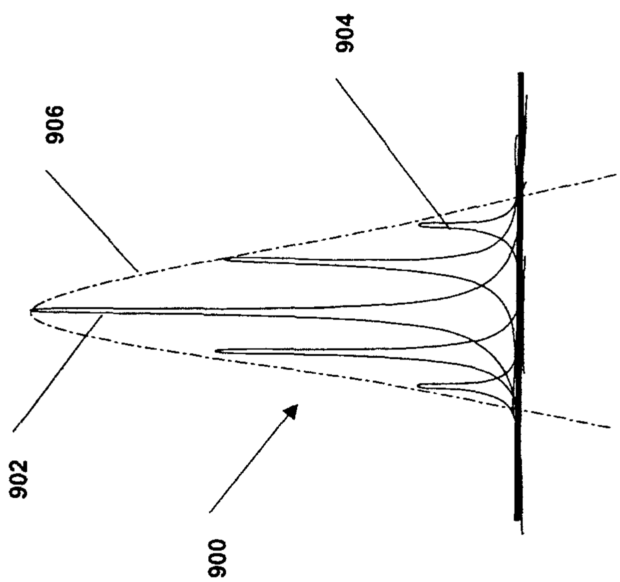


Fig. 11

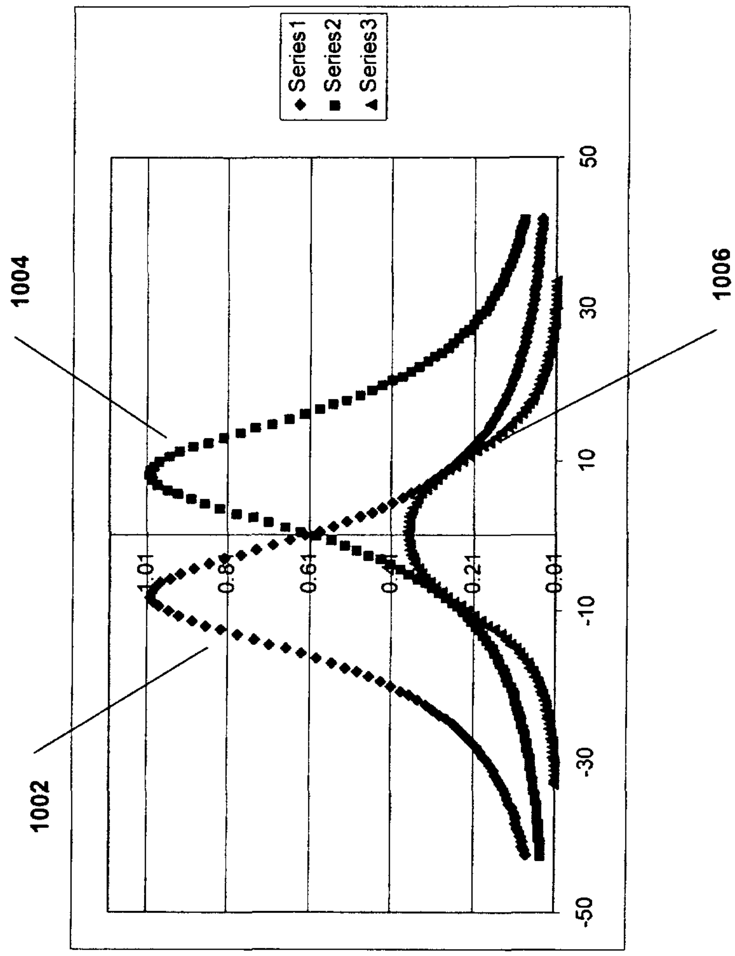
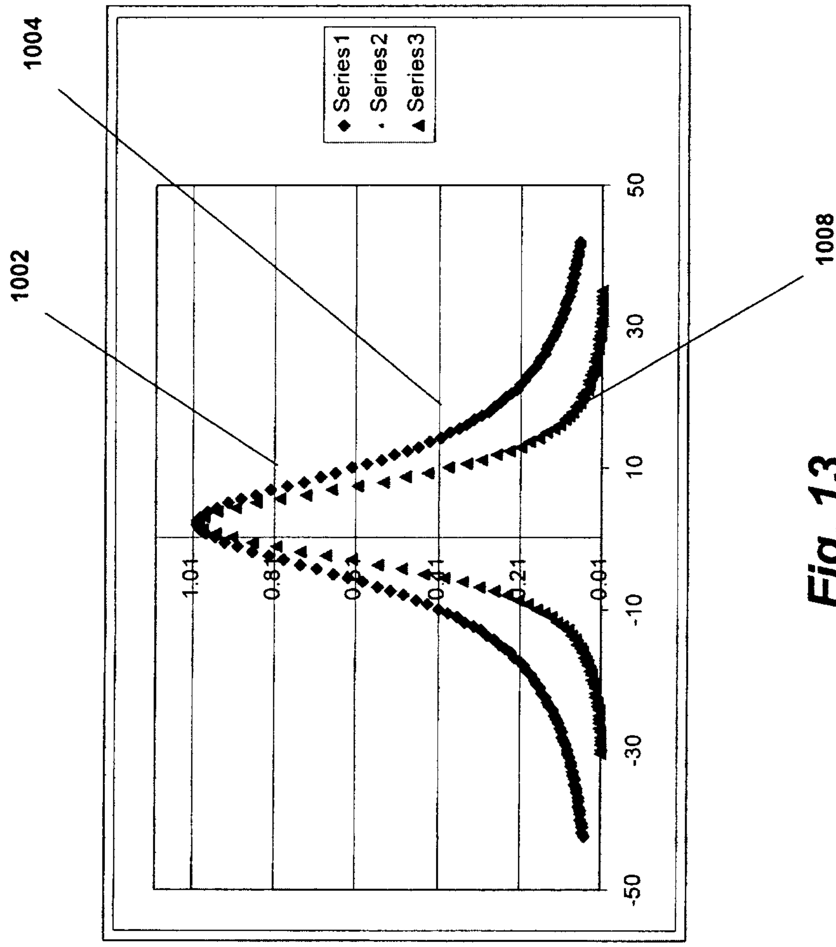

1002
1004
1006
Series1
Series2
Series3
1.01
0.81
0.61
0.41
0.21
0.01
-50
-30
-10
10
30
50

Fig. 12


1002
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1008
Series1
Series2
Series3
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0.21
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-50
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-10
10
30
50

Fig. 13

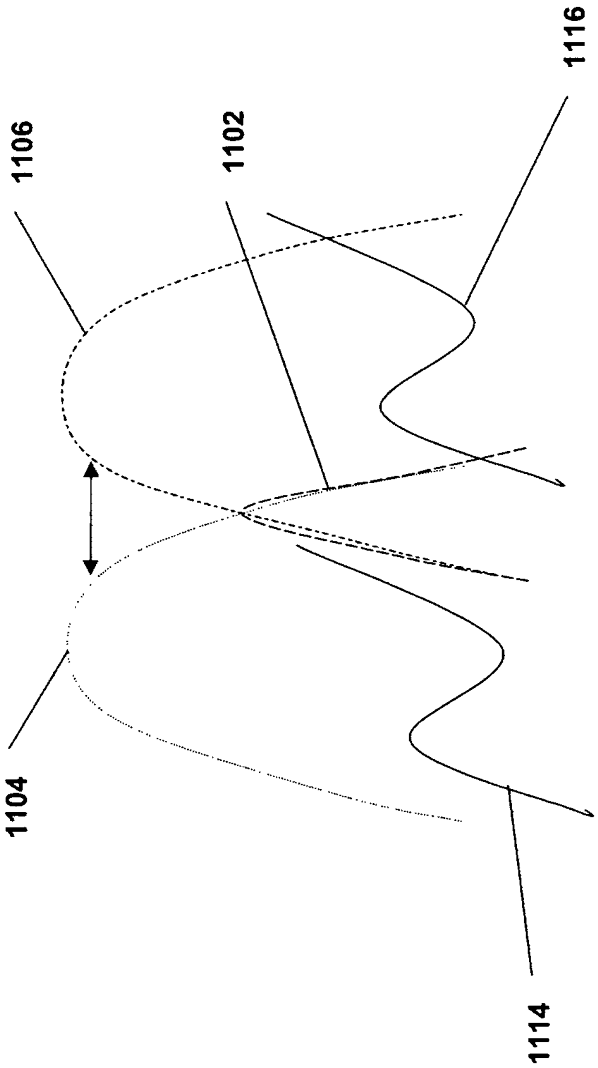

Fig. 14

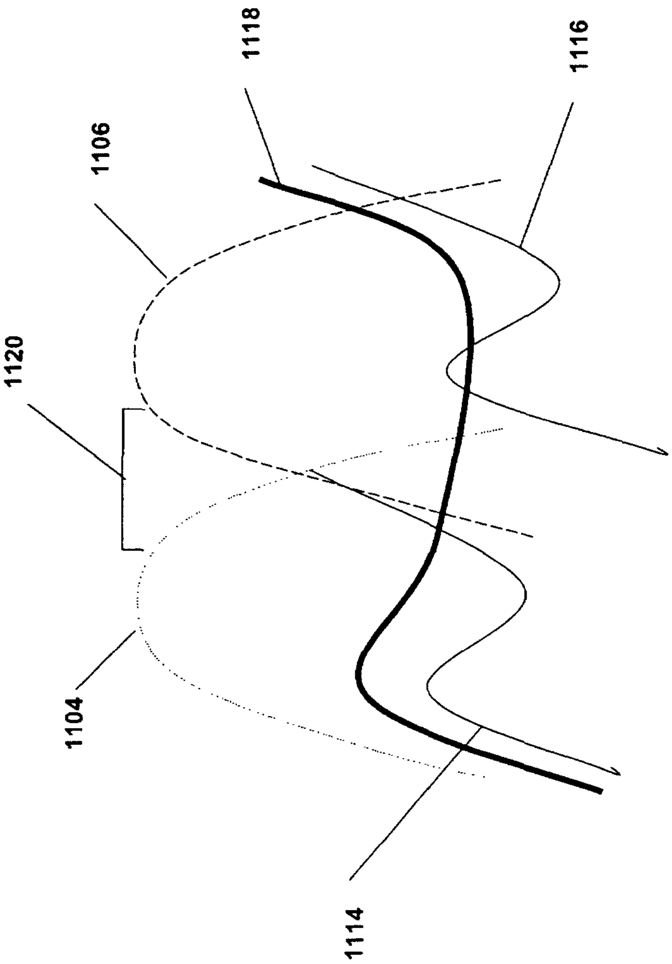

Fig. 15

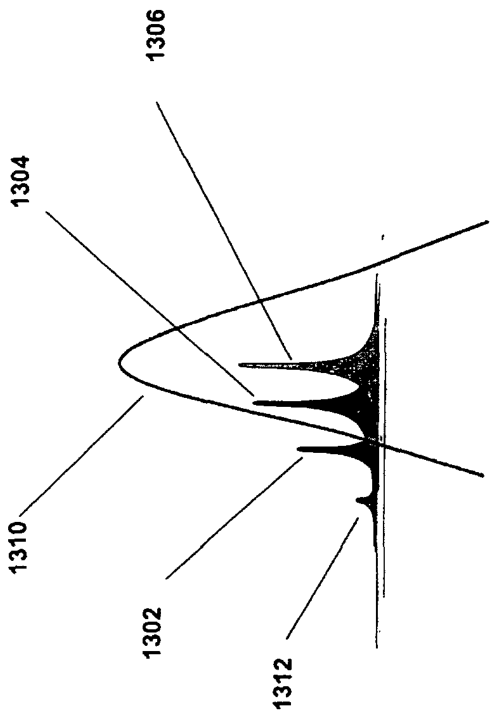

Fig. 16

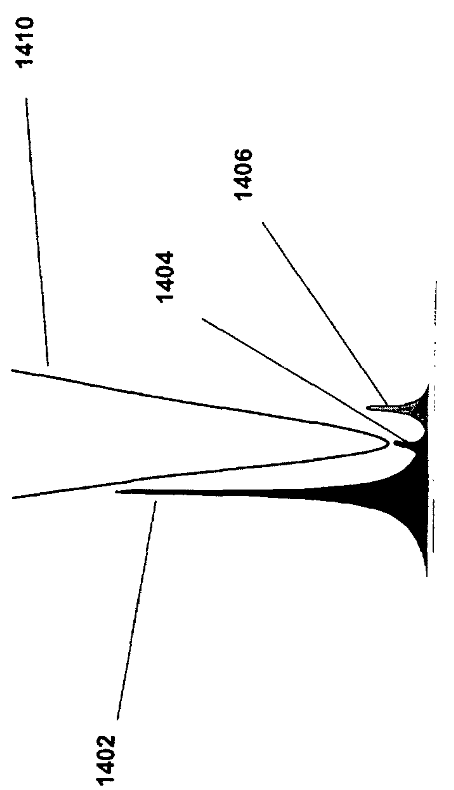

Fig. 17

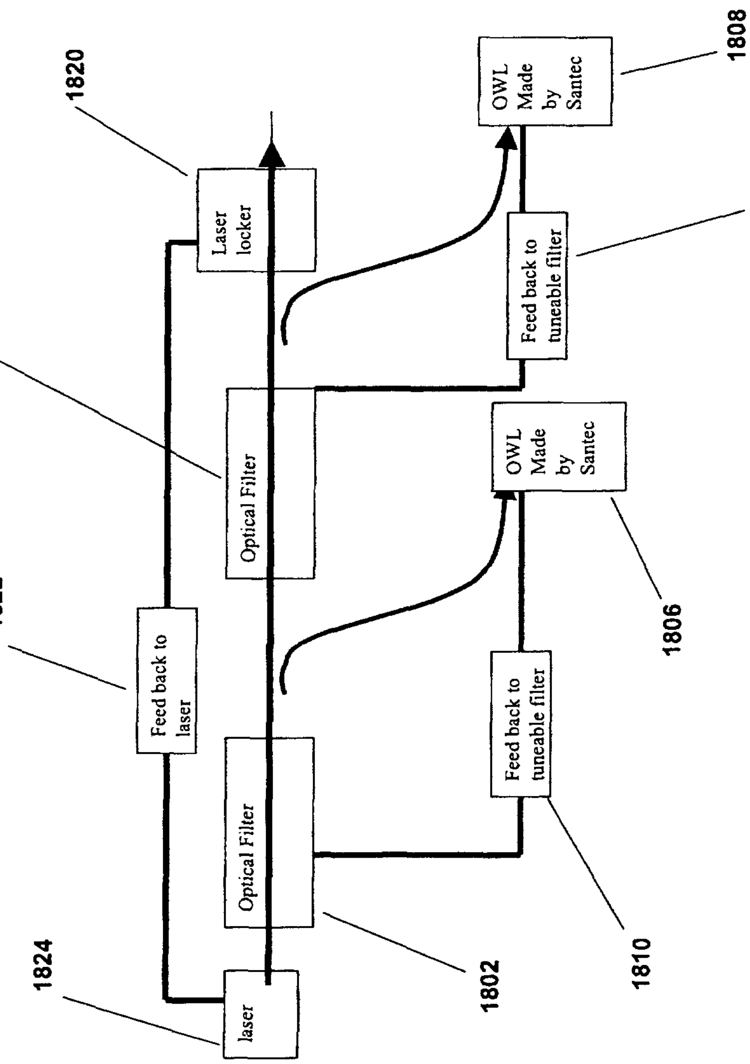
laser
Optical Filter
Optical Filter
Feed back to laser
Laser locker
Feed back to tuneable filter
Feed back to tuneable filter
OWL Made by Santec
OWL Made by Santec
1802
1804
1806
1808
1810
1812
1820
1822
1824

Fig. 18