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O'Meara [45] May 1, 1973

[54] ADAPTIVE ARRAYS

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[52] U.S. Cl. ....250/199, 343/7.5, 343/100 TD, 356/5, 356/152
[51] Int. Cl. H04b 9/00
[58] Field of Search ....250/199; 325/154, 325/159, 180, 368, 369, 56; 343/7 A, 7.5, 17.5, 100 SA, 100 TD, 854, 208; 356/4, 5, 28, 152

[56] **References Cited**

UNITED STATES PATENTS

3,174,150	3/1965	Sferrazza	343/100
3,267,380	8/1966	Adams	325/56
3,394,374	7/1968	Weiss	343/100 TD
3,611,381	10/1971	Preischat	343/100 TD

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[57] **ABSTRACT**

Herein are disclosed multiple beam laser systems with adaptive phase control for establishing, at a target, an in-phase condition between the corresponding electromagnetic fields of all the beams. Phase modulation at different frequencies or differing waveforms is applied in the transmission paths of selected radiating elements of the array; and modulation components in the received energy are utilized to control phase shifters in the transmission paths so as to maintain the cophase condition at the target.

7 Claims, 6 Drawing Figures

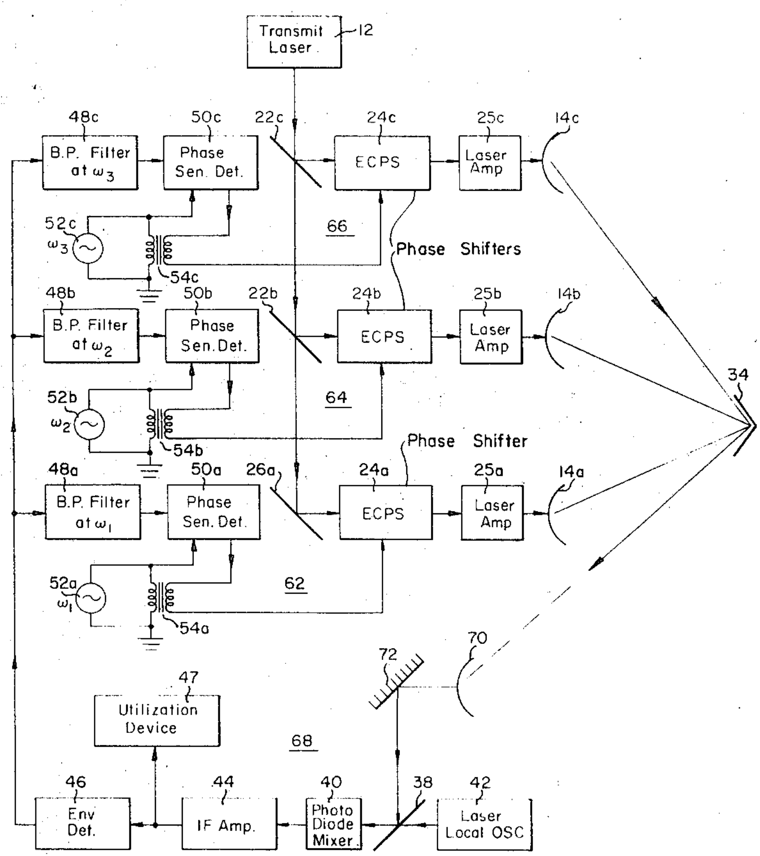
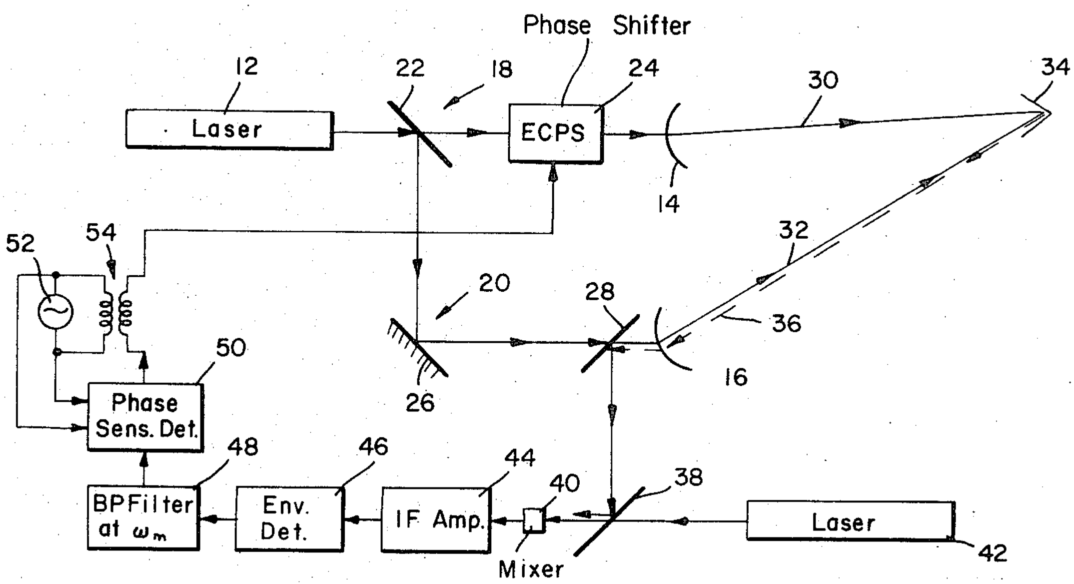


Fig. 1.



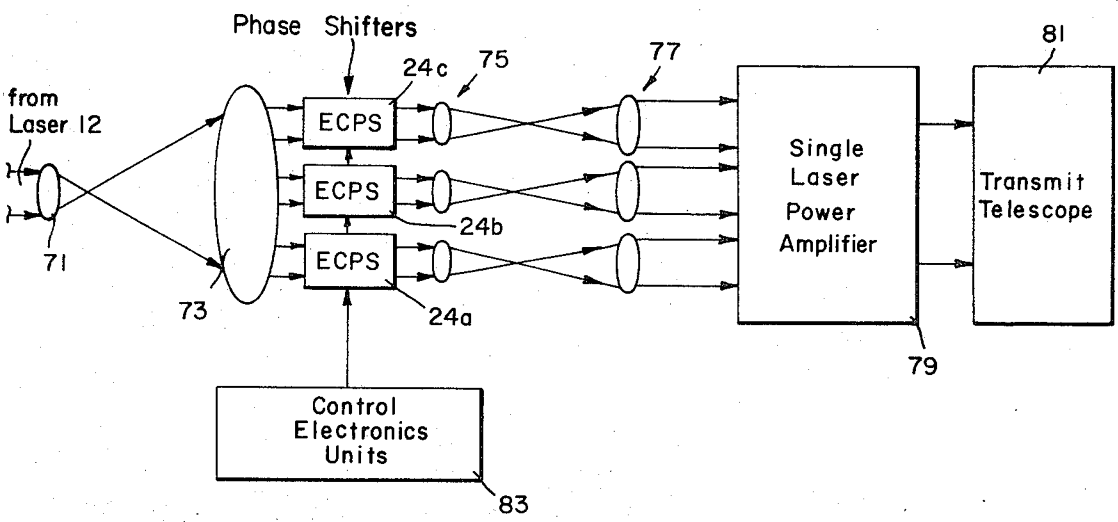


Fig. 6.

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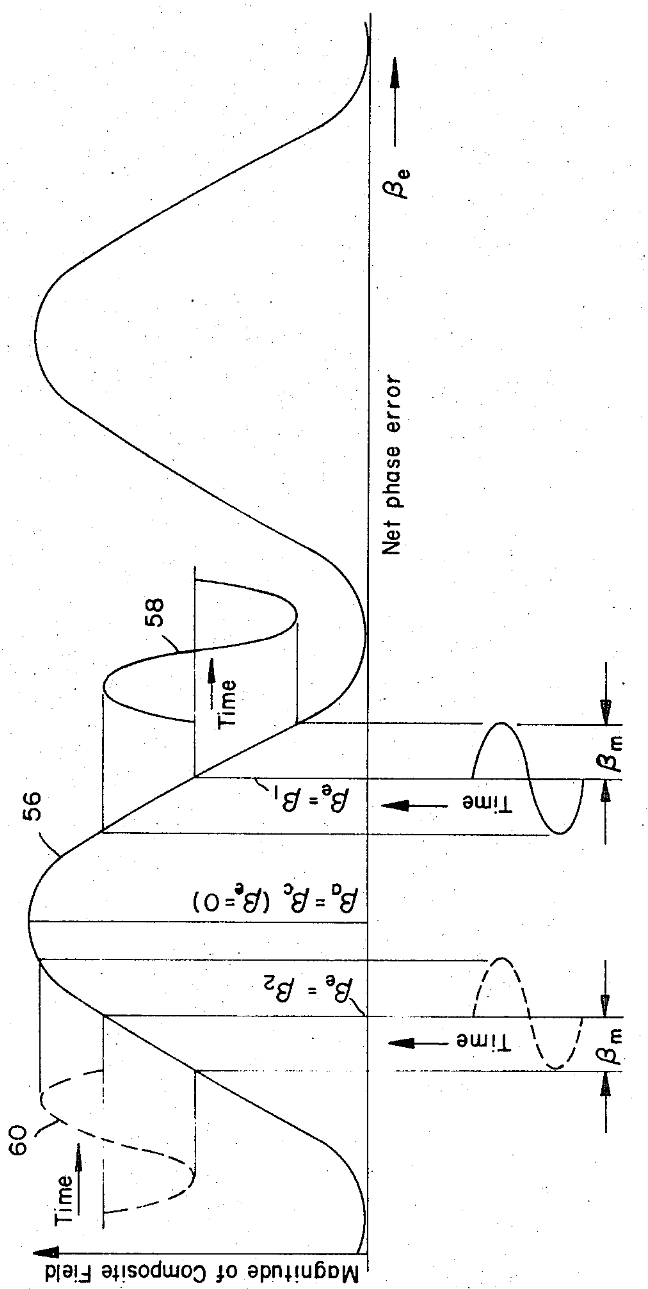
Magnitude of Composite Field
Net phase error
βe
56
58
60
Time
Time
Time
Time
βe = β1
βe = β2
βa = βc (βe=0)
βm
βm

Fig. 2.

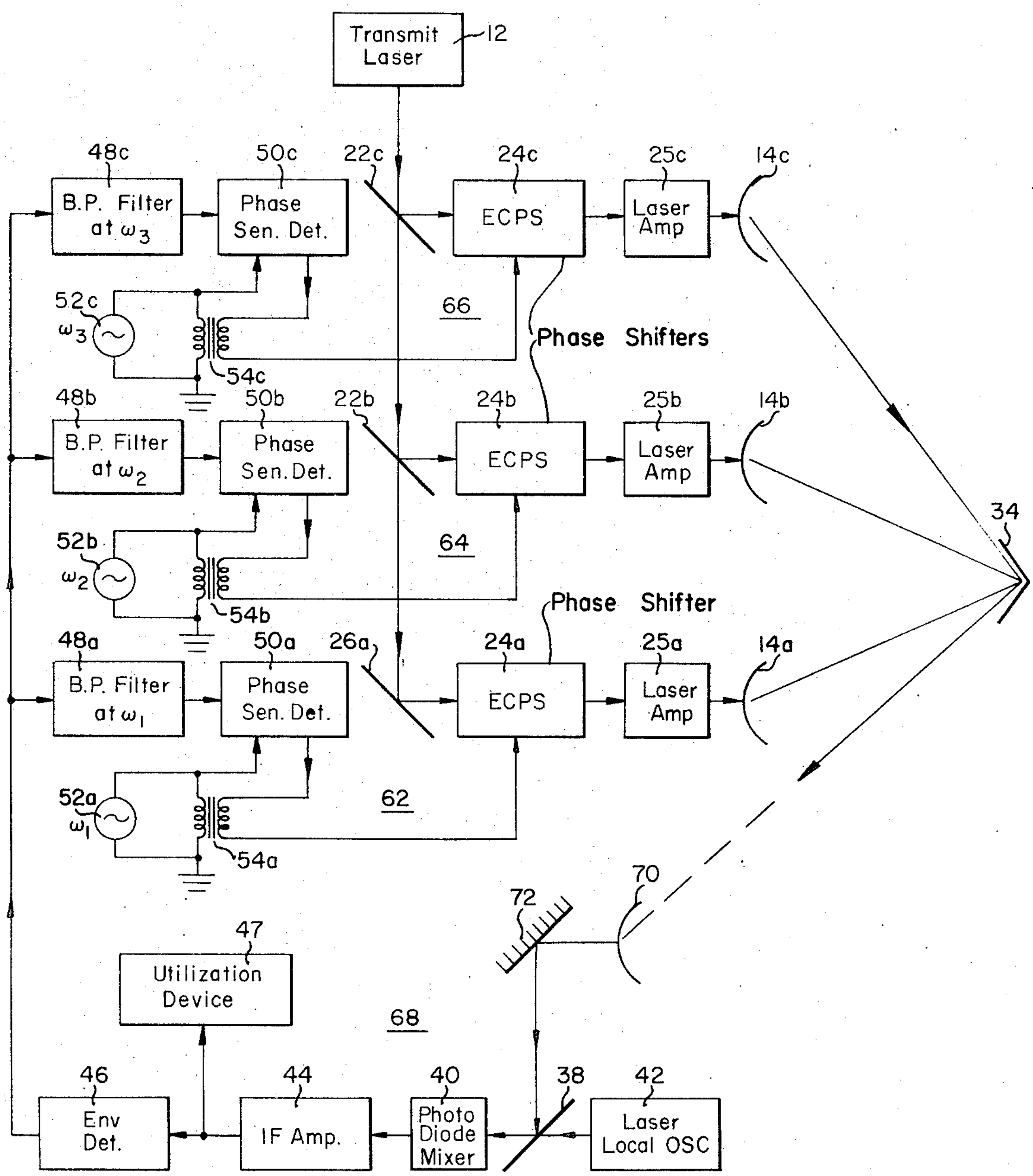
Transmit Laser
12
48c
50c
22c
24c
25c
14c
B.P. Filter at ω_3
Phase Sen. Det.
ECPS
Laser Amp
52c
ω_3
66
Phase Shifters
54c
48b
50b
22b
24b
25b
14b
B.P. Filter at ω_2
Phase Sen. Det.
ECPS
Laser Amp
52b
ω_2
64
34
54b
Phase Shifter
48a
50a
26a
24a
25a
14a
B.P. Filter at ω_1
Phase Sen. Det.
ECPS
Laser Amp
52a
ω_1
62
54a
70
72
47
Utilization Device
68
46
44
40
38
42
Env Det.
IF Amp.
Photo Diode Mixer
Laser Local OSC

Fig. 3.

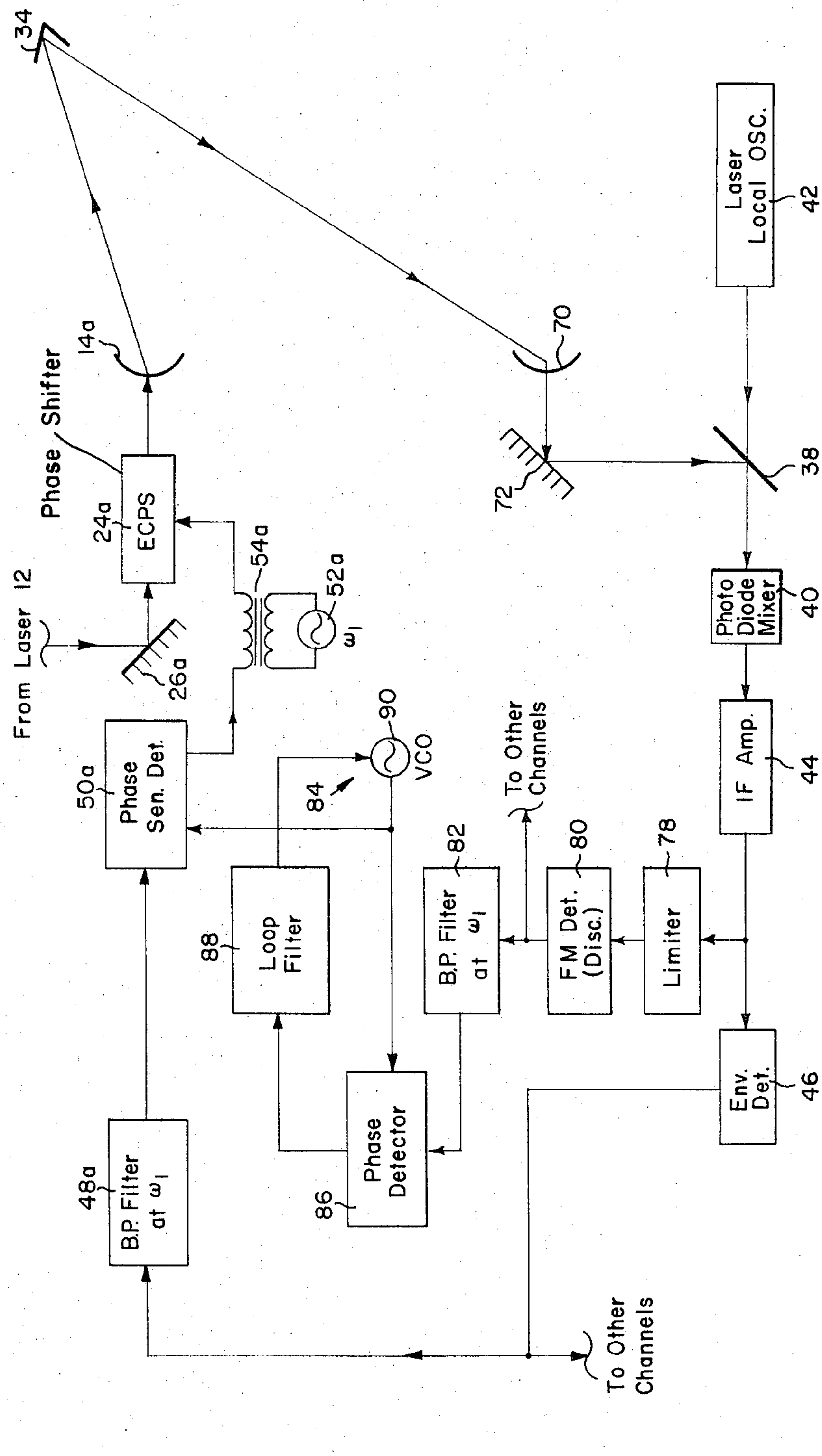
34
14a
Phase Shifter
24a
ECPS
From Laser 12
26a
54a
52a
ω_1
50a
Phase Sen. Det.
90
VCO
84
88
Loop Filter
86
Phase Detector
48a
B.P. Filter at ω_1
To Other Channels
82
B.P. Filter at ω_1
80
FM Det. (Disc.)
78
Limiter
70
72
Laser Local OSC.
42
38
Photo Diode Mixer
40
IF Amp.
44
Env. Det.
46
To Other Channels

Fig. 4.

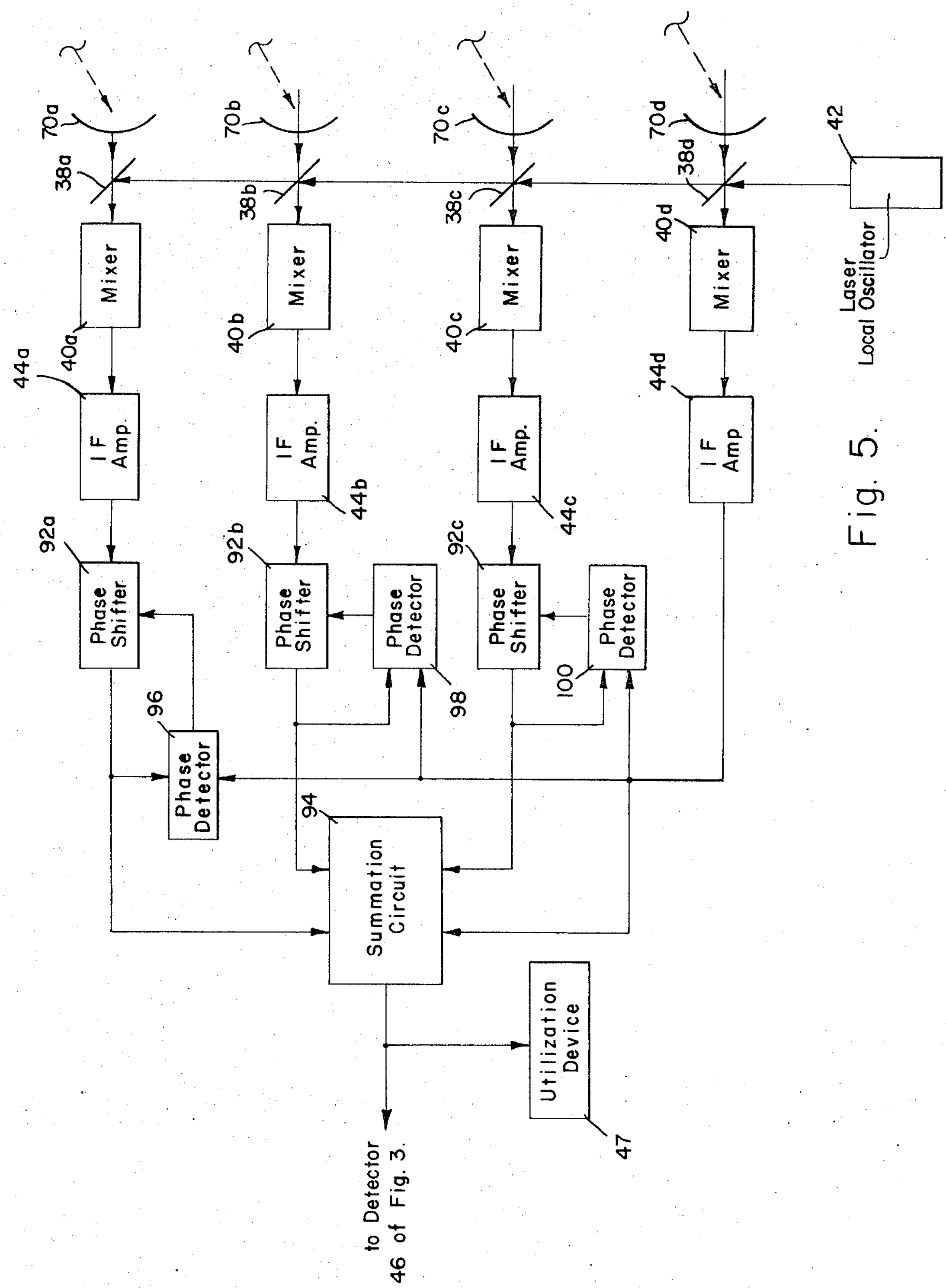
70a
70b
70c
70d
38a
38b
38c
38d
42
Laser
Local Oscillator
40a
40b
40c
40d
Mixer
Mixer
Mixer
Mixer
44a
44b
44c
44d
I F
Amp.
I F
Amp.
I F
Amp.
I F
Amp
92a
92b
92c
Phase
Shifter
Phase
Shifter
Phase
Shifter
96
98
100
Phase
Detector
Phase
Detector
Phase
Detector
94
Summation
Circuit
Utilization
Device
47
to Detector
46 of Fig. 3.

Fig. 5.

ADAPTIVE ARRAYS

BACKGROUND OF THE INVENTION

This invention relates generally to adaptive arrays and particularly to such arrays wherein the relative phase of energy transmitted by a plurality of radiating elements is controlled to establish an in-phase condition at the target.

The distribution of electromagnetic energy radiated by an aperture immersed in the atmosphere differs from the ideal diffraction limited behavior (assumes a vacuum) due to refractive index inhomogeneities caused by variations in atmospheric density. The angular width of the main lobe, its direction, and the intensity distribution within the lobe are all affected by these density variations. Among the principal sources of density variation are atmospheric turbulence and the heating caused by absorption of the radiated energy. In the case of atmospheric turbulence, the effect of the inhomogeneities depends on the strength of the turbulence and on the path length. As the strength of the turbulence and/or the path length increases, the first noticeable effects are changes in the direction of the beam (beam wander) and those associated with the random phase shift introduced across the beam (loss of coherence). The distribution of the radiated energy departs appreciably from the ideal when the energy radiated from different parts of the aperture is no longer phase coherent at the receiving point.

For example, the performance of very narrow beam width (large aperture) coherent laser systems operating through the atmosphere is seriously degraded by atmospheric turbulence and also in some cases by nonlinear propagation effects. Three turbulence related propagation effects are: the width of the main lobe of the radiation pattern is increased, reducing both resolution capability and power on target; the direction of the main lobe deviates from that predicted under free space conditions, and is not constant in time; and the shape of the radiation pattern may become highly irregular and time varying.

It is possible to reduce the deleterious effects of the atmosphere on the radiation pattern of a large aperture by utilizing instead, an array of smaller apertures whose phase is adaptively controlled. If each of the individual elements in the array are small enough that their radiation pattern is diffraction limited, near diffraction limited performance from the entire array may be obtained by adaptively changing the relative phase of the excitation sources driving various radiation elements, in such a manner that the atmospheric effects are compensated. The implementation of this concept requires the capability of sensing and changing the relative phase of the radiated energy at the target.

One adaptive compensation technique uses the phase difference between signals from multiple receiving channels, as determined by phase comparison of the optical carrier frequencies (after heterodyne conversion), to control the required phase adjustments of the transmitted beams. Although this technique may be a marked improvement over nonadaptive systems, it does not provide direct confirmation of a cophase condition at the target. For example, if a phase measurement error due to a path unbalanced exists in the system, then a cophase condition will not be established at the target and hence atmospheric conditions are not fully compensated for by this technique. Additionally, this "phase comparison between receiving channels" approach requires heterodyne detection that introduces mechanization difficulties, especially when targets of high doppler signatures are involved; and further problems are encountered with targets at such ranges that backscattered energy is comparable to energy reflected from the target.

SUMMARY OF THE INVENTION

It is therefore an object of the subject invention to reduce the deleterious effects of the atmosphere on the radiation pattern of a large aperture by utilizing instead an array of smaller apertures which are adaptively controlled to maintain the plurality of transmitted beams "in-phase" at the target.

Another object of the subject invention is to provide an adaptive array which directly senses the establishment of the cophase condition of all the transmitted beams at the target.

A further object is to provide an adaptive array which does not require a phase-matched, multi-channel, heterodyne receiver system.

Still another object is to provide an adaptive array which may be used with systems having a single receiving channel that need not have any common paths with any one of the transmitting channels.

Yet another object is to provide an adaptive array wherein the defocusing effect of moving targets is substantially reduced.

In accordance with one preferred embodiment of the subject invention, a dithering of variable phase shifters associated with the radiating elements of an optical transmission array is employed such that each of the transmitted beams is phase modulated at a separate characteristic dither frequency. On reception of the energy from a target, envelope detectors and filters centered at each of the dither frequencies provide signals for controlling a compensating phase shifter in each transmitting channel to provide an in-phase condition of all radiated fields at the reflecting target. For each transmitting beam, the magnitude of the amplitude modulation components in the received energy at the associated dither frequency is indicative of the deviation of the phasing of its electromagnetic fields from a cophase condition at the target. The phase of the received amplitude modulated signals is indicative of the polarity of the phase error of the associated transmission channel.

The subject invention eliminates problems encountered by other systems for adaptively controlling arrays in that the cophase condition at the target is measured directly. Since the radiated field from each aperture element of the array is characterized by its own signature — its dither frequency — separation of the received information into path error components associated with one and only one path is easier to mechanize and it does not require heterodyne detection or complex computations.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features of this invention, as well as the invention itself, will be better understood from the accompanying description taken in connection with the accompanying drawings in which like reference characters refer to like parts and in which:

FIG. 1 is a block diagram of a laser transmitting and receiving system having an array adaptively controlled to establish a cophase condition at the target, in accordance with the principles of the subject invention;

FIG. 2 is a diagram of the composite electromagnetic field at the target, for explaining the phase to amplitude conversion process utilized by the adaptive arrays of the subject invention;

FIG. 3 is a block diagram of a laser transmitting and receiving system wherein each transmitting element of the array is adaptively controlled for establishing an "in-phase" condition of the energy at the target;

FIG. 4 is a block diagram of a portion of the laser system of FIG. 3 with additional circuitry for maintaining an accurate phase reference independently of target range;

FIG. 5 is a block diagram of a phase compensated receiver that may be incorporated into the systems of FIGS. 1, 3 or 4; and

FIG. 6 is an optical array system which utilizes a single laser power amplifier and telescope for transmitting a plurality of adaptively controlled beams.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The subject invention may be best understood by first considering the basic two element array of FIG. 1. As there shown, the laser 12 excites transmitting aperture elements 14 and 16 by means of transmission paths 18 and 20, respectively. Path 18 includes a power or beam splitter element 22 and an electronically controllable phase shifter 24. Path 20 includes beam splitter 22, a mirror 26 and a beam splitter 28.

Transmitting apertures 14 and 16, which may include focusing optics such as telescopes, radiate beams 30 and 32 respectively, so as to illuminate a target 34. A portion of the total energy reflected from target 34, shown as beam 36, is received by aperture 16 and is applied by means of beam splitters 28 and 38 to a mixer photodiode 40. This received energy is heterodyned in mixer 40 with an optical frequency signal supplied by a laser 42, and is amplified in an IF amplifier 44. The output signal from amplifier 44 is processed by an envelope detector 46 which produces an output signal that varies in amplitude in accordance with the envelope of the IF signal from amplifier 44.

The signal from detector 46 is processed by a passband filter 48 centered at a frequency ω_m, and the output therefrom is applied as one input to a phase sensitive detector 50. The signal from phase detector 50 has an amplitude A sin ϕ, where A is a function of the magnitude of the signal applied from filter 50 and ϕ is the phase angle between this last mentioned signal and a reference signal ω_m applied from a reference oscillator 52.

The signal from phase detector 50 is summed with the reference signal ω_m by means of a transformer device 54; and this summed signal is applied to an electronically controllable phase shifter 24. Phase shifter 24, which may be a movable mirror or an electro-optical device, for example, varies the effective transmission path length (or net phase shift) 18 in response to the signal applied thereto.

The optical signals which excite aperture elements 14 and 16 are of a common frequency but generally are not in phase. These two aperture elements radiate energy to a common target 34, and the fields from each of these elements generally experience a further differential phase shift at the target because of path length differences. The composite signal at target 34 may be expressed as,

$$E_r = A_r\,[\cos(\omega_c t) + \cos(\omega_c t + \beta_o)] \quad (1)$$

or

$$E_r = 2A_r \cos\beta_o \cos(\omega_c t + \beta_{0/2}) \quad (2)$$

where ω_c id the frequency of laser 12 and β_o is the composite differential phase error. The constructive (or destructive) interference of the two field components yields a spatial interference pattern with a sinusoidal envelope 56 (FIG. 2). For those cases where β_o varies with time, the spatial interference pattern wanders back and forth over the target region.

The modulation of electronically controllable phase shifter 24 produces a phase excursion,

$$\psi_{ps}(t) = -\beta_c + \beta_m \sin\omega_m t \quad (3)$$

where β_c is a corrective (unmodulated) phase shift applied from detector 50 to provide the desired phase adjustment. The net phase error β_o at target 34 is also dithered over this same range; that is,

$$\beta_o = \beta_a - \beta_c + \beta_m \sin\omega_m(t) \quad (4)$$

where β_a is the atmospheric (or other) phase error to be corrected by β_c. As a consequence, the interference pattern dithers back and forth over the target. Thus, the phase modulation produced by phase shifter 24, introduces an amplitude modulation at the dither frequency, in the composite signal on target and hence in the received return signal.

From another viewpoint, that of a fixed point β_o, the envelope modulation process of Equation 3 is also illustrated in FIG. 2. For a phase error β_1 to the right of the envelope peak ($\beta_a = \beta_c$) of phase error curve 56, the modulation envelope 58 is in phase with the dither source (oscillator 52 in FIG. 1). For a phase error β_2 to the left of the modulation envelope, the modulation envelope 60 is 180° out-of-phase. For $\beta_a = \beta_c$ the fundamental component of the modulation envelope vanishes. Thus, the array of FIG. 1 has the required characteristics for a feedback control system whereby the mean value of phase shifter 24, β_c, is controlled such that $\beta_a - \beta_c$ is driven to zero, thereby establishing the cophase condition at the target 34. In particular it is noted that the magnitude and plurality of the output signal of phase detector 50 is such as to force the mean phase value of path 18 to establish the cophase condition at the target.

The extension of the target cophasing concept of the subject invention to more than one phase controlled transmission path is illustrated in FIG. 3. In FIG. 3, each of the elements of the various transmission paths is given the same numeral designation as the corresponding element of transmission path 18 of FIG. 1 with the letter *a*, *b* and *c* identifying the elements associated with transmission paths 62, 64 and 66 respectively. Also in FIG. 3 laser amplifier 25 has been coupled in each of the transmission paths between the phase shifters **24** and the aperture elements **14**. Additionally, the received channel or signal path **68** is illustrated (for generality) in FIG. **3** with a separate receiving aperture **70** and beam directing mirror **72** associated therewith. In the operation of the system shown in FIG. 3, the phase of each electronically controllable phase shifter (**24***a*, **24***b* and **24***c*) is dithered at its own characteristic frequency ω_m. The corresponding amplitude modulation component in the reflected return signal (as explained above relative to FIG. **2**) is separated, after detection, from the IF carrier by envelope detector **48**; and from the other modulation frequency components by means of bandpass filters centered on frequency ω_m. Therefore the phase correction offset, Δ_c, introduced by each of the electronically controllable phase shifters is a function of the modulation caused by the dither of that phase shifter only. The output signal of IF amplifier **46** is also coupled to a utilization device **47** which may be a display or computer unit, for example, and which utilizes the target information contained therein.

It is noted that the single reference channel technique of the system of FIG. **1** uses one of the transmission paths as an uncontrolled reference and the phase of the controlled channel is adjusted to establish the cophase condition at the target. When this approach is extended to a large group of adaptively controlled radiating apertures, the extraction of the desired error information associated with each of the adaptive channels by simple filtering is complicated. This is due to intermodulation products resulting from the interaction of the phase modulation applied to each of the plurality of transmitted beams. One approach for avoiding this intermodulation problem is a sequential switching technique such that only the reference element and one other element then being established in phase synchronism, are radiating. After proper phasing is established for a particular controlled channel it is turned off and the same operation is repeated with the other channels. This switching sequence is performed at a repetition frequency high enough that the sequence may be completed before there is any substantial change in the required phase corrections. Since each transmitting channel is cophased to the reference before a next element is turned on, it would not be necessary to turn off the preceding elements. Therefore each element of the array may be phase adjusted by a sequence which activates each of the controlled transmitting channels one at a time.

As an alternative to the technique wherein the phase of each controlled transmission path is determined with respect to a reference channel, the system of FIG. 3 measures and corrects the average phase error in each transmission path as compared to all other channels considered simultaneously. In the mechanization of FIG. **3**, the synchronously detected component at a frequency ω_m is a measure of the average of the sine of the phase errors of channel m compared to all other channels. Each error signal S_{Dm} (from the m^{th} phase sensitive detector) can then be employed to correct the phase error in the m^{th} channel (feeding the m^{th} radiating aperture). The distrubuted reference syst em of FIG. **3** has one important advantage in that the loss of any one signal component ($A_m = 0$) as a result of propagation or equipment failure does not destroy the operation effectiveness of the remaining channels. The operation of the distributed reference system may be compared to the common homodyne detection process. For this comparison the signal input is analogous to the phase modulated signal from a particular transmitting channel, while the function of a reference oscillator is performed by the phasor sum of the ensemble of the remaining channels, as returned from the target.

The subject invention may be utilized to compensate for frequency errors as well as phase error corrections inasmuch as frequency errors may be considered as phase errors which increase approximately as a linear function of time. Such frequency errors could result from oscillator drifts or differential doppler shifts, for example. As used herein the term "differential doppler shift" means the difference in the doppler frequencies between transmitted beams.

Although in the transmission systems shown in FIGS. **1** and **3**, the energy radiating from each of the transmitting apertures originates from a common laser source, in an alternate embodiment a separate laser oscillator may be used in each of the transmitting channels. The operation of the system would remain unchanged except that the correction voltages, S_{Dm}, would be applied to a frequency controlling element, such as a mirror internal to the laser cavity, rather than a phase controlling element. This technique circumvents the accumulation of excess phase shift by changing the transmitted frequency of each array element to compensate for frequency errors. An increase in cost may be associated with this mechanization due to the need for a plurality of laser oscillators, although the beam splitting elements would be eliminated. Also, each laser oscillator would have to be supplied with its own "self-stabilizing loop" to control its frequency during search and acquisition of targets. The frequency stability of the plurality of lasers must be such that they stay within the "capture range" of the control loops.

If the dither phase modulation frequencies (ω_m) are selected too low then there is the possibility of interference from target or atmospheric scintillation modulations. On the other hand, if the labeling (tagging) modulations employed are too high a problem with the phase synchronization between the dither signal reference and the return signal may result. Hereinabove for the purposes of explaining the fundamental principles of the invention it has been assumed that either the beam labeling frequencies (ω_m) were sufficiently low, or that the propagation paths are sufficiently short that for all practical purposes the phase detection operation could be considered to be synchronous. That is, it was assumed that there was no time slip or phase error between the received input signal to the phase sensitive detector, such as detector **50***a* of FIG. 3, for example, and the reference signal applied from the reference oscillator, such as **52***a*.

In the more general case, where there exists a substantial round trip delay τ in the received signal, the control voltage S_{Dm} from the m^{th} phase detector is a function of cos ($\omega_m\tau$). If $\omega_m\tau$ becomes as large as $\pi/4$ the signal S_{Dm} vanishes independently of phasing errors at the target. If $\omega_m\tau$ equals πI, where I is an odd integer, the sign of the error signal S_{Dm} reverses and the system will "lock on" the minima rather than the maxima of the composite beam (56 of FIG. 2). Therefore, in an uncompensated system the value of $\omega_m\tau$ must be restricted. Such a limitation on the value of the term $\omega_m\tau$ determines the highest permissible value of ω_m for a given maximum range. Since high modulation frequencies are sometimes desirable to minimize noise interference problems or to accommodate large frequency errors it may be desirable to incorporate techniques to compensate for the round trip delay time (τ).

One method of compensating for the time displacement between the reference signal to the synchronous detector (phase sensitive detector 50, for example) and the return modulated envelope (waveform 58 of FIG. 2) would be by knowing or measuring the range to the target and computing the associated phase delay value. This phase shift could then be compensated by introducing a phase delay correction in the path of the reference signal to the synchronous detector.

A more generally applicable method of compensating for the loss of synchronism between the reference to the control loop phase detector and the modulated return signal is to transmit the reference dither frequency (ω_m) in the form of modulation on some carrier and to process the associated return signal so that this transmitted reference may be used as the reference for the synchronous detector. Since both the input signal to the phase sensitive detector and the reference thereto would then experience the same path delays, a purely synchronous detection operation can be obtained independently of the value of the term $\omega_m\tau$. For the system such as shown in FIG. 3, the most convenient choice for carrier and modulation types would be those which are already present, that is, phase or frequency modulation of the optical carriers. FIG. 4 shows one transmit channel and the received channel of FIG. 3 modified to compensate for the above described synchronization problem. The transmitted channel in FIG. 4 is designated generally by the reference numeral 62′ and elements thereof corresponding to like or similar element of channel 62 of FIG. 3 are, in FIG. 4, identified by like reference numerals. Only one modified transmission channel is illustrated in FIG. 4 for explaining the transmission path delay compensation technique. However, in practice the compensation modifications would be incorporated into each of the transmission channels such as channel 64 and 66 of FIG. 3, in a manner identical to that to be described for channel 62′.

Referring now primarily to FIG. 4, optical energy from laser 12 (FIG. 3) is modulated by electronically controllable phase shifter 24*a* and transmitted by aperture 14*a*. The energy transmitted from aperture 14*a* along with the energy from the other transmitting apertures (not shown in FIG. 4) is reflected from target 34. A portion of this reflected energy is intercepted by antenna 70 and processed by means of mirror 72, beam splitter 38, photodiode mixer 40 and laser local oscillator 42 in the same manner as described relative to FIG. 3. The output of mixer 40 after being processed by IF amplifier 46 is applied in parallel to an envelope detector 48 and a limiter 78. The limiter 78 removes the envelope modulation effects and the output signal therefrom is demodulated by means of a conventional frequency discriminator 80. The output from discriminator 80 is applied in parallel to a bandpass filter 82 at a frequency ω_1, associated with the transmission channel 62′, as well as to similar filters which are at the frequencies associated with the remaining transmitting channels (not shown). For example, if a channel 64′ and 66′ were shown the output of frequency discriminator 80 would also be processed by bandpass filters at frequencies ω_2 and ω_3, respectively.

The output signal of frequency discriminator 80 contains all of the labeling frequencies (ω_m) with a time delay corresponding to the transmission-reception path of the received signal. The output signals from the bandpass filters, such as filter 82 associated with transmission channel 62′, could be used to reference the phase sensitive detectors, such as 50*a*, of the associated channel. In the embodiment of FIG. 4, however, the output of the bandpass filter is utilized to control a "phase locked loop" 84 which includes a phase detector 86, a loop filter 88 and a voltage controlled oscillator 90. The phase detector 86 compares the phase between the oscillator 90 and the output signal from the filter 82; and the output signal of phase detector 86, after being processed by loop filter 88, is used to adjust the voltage controlled oscillator 90 such that the frequency and phase of oscillator 90 tracks the signal from filter 82. The output signal from the oscillator 90 is also applied to the phase sensitive detector 50*a* wherein it is utilized as a reference for the received, modulated signal associated with the frequency ω_1 applied to detector 50*a* through the filter 48a.

The output signal of phase sensitive detector 50*a* is summed with the signal of a reference oscillator 52*a* by means of a transformer device 54*a*. This summed signal is applied to control electronically controllable phase shifters 24*a* to apply phase modulation to the transmitted signal at the labeling frequency ω_1; and to adjust the mean value of the phase of the channel such that it is in phase with the other transmission channels (not shown in FIG. 4) at the target 34.

As is now evident, the systems in accordance with the subject invention function equally well with a separate or even remotely located receiving aperture. This characteristic is desirable in certain applications for a number of reasons, not the least of which are the elimination of back-scattering and crosscoupling problems inherent in systems that transmit and receive from the same apertures. However, a certain amount of economy is sometimes realized by the transmitting and receiving systems sharing apertures and the subject system is of course adaptable to a common transmit and receive mechanization, if so desired.

In some mechanizations it may be desirable to extend the size of the receiving aperture beyond its coherent length in order to improve signal-to-noise ratios for distance targets. In such cases adaptive control of a receiving array may be employed.

One approach to adaptive control of the receiving system, if common transmission and receiving apertures are employed, would be to use the phase error information, S_{Dm}, extracted from the transmitter control portion of a multi-dither system to correct (in an open-loop manner) for the phase errors in the received paths. However, this approach suffers from the problem that the transmitter system corrects for all phase errors in the transmission path including any laser power amplifiers that may be utilized, as well as those in the post-aperture radiation paths. Also, since such an approach requires media linearity it is restricted to low levels of transmitter power.

Another approach is to employ an adaptively controlled receiving system with a separate phase modulation labeling frequencies associate with each receiving channel in a manner analogous to the above described transmitter system. However, this method requires the doubling of the number of dither frequencies on transmission and thereby increases the problem of avoiding possible intermodulations.

The method of adaptively controlling a plurality of receiving channels which may be best adapted to a large variety of applications involves measuring the phase differences between IF receiver channels and using this difference to control phase shifters in the received channels such that the phase differences between channels are driven to zero. One such mechanization is shown in FIG. **5** wherein a plurality of receiving apertures corresponding to the aperture **70** of FIGS. **3** and **4** are designated by reference numerals **70***a*, **70***b*, **70***c* and **70***d*. In like manner the IF amplifiers for each channel which would correspond to amplifier **44** in the previously described embodiments are given the same reference numeral with a postscript corresponding to the particular channel. In the embodiment of FIG. **5** varactor diode phase shifters are inserted following the IF amplifiers in each controlled channel prior to a summation circuit **94**. Summation circuit **94** forms the sum of the received signals which have previously been translated to the intermediate frequency zone and phase adjusted to be in phase. The varactor phase shifters associated with each of the controlled receiving channels are designated by the reference numeral **92** with the postscript of the corresponding channel. Phase detector **96** compares the phase differences between channel d and channel a and drives the phase shifter **92***a* to null this difference. Similarly, phase detector **98** compares the phase difference between channels *b* and *d* and controls phase shifter **92***b* in response thereto; and phase detector **100** compares channels *c* and *d* and controls phase shifter **92***c*. Hence the circuit of FIG. **5** adjusts the phase of the received signals to a cophase condition prior to their summation in circuit **94**. The output signal from summation circuit **94** may be applied to a utilization device **47**, such as a display or computation system, as well as to envelope detector **46** (FIG. **3**) which feeds the transmitter control loops.

In the disclosed embodiments heterodyne detection (mixer **40**) was utilized because in general the detection is better than if video detection without prior IF amplification were used. However, the subject invention is equally well adapted to noncoherent detection and in some applications such as those involving high doppler frequency shifts, for example, noncoherent detection may be preferred. For example, heterodyne detection systems require either that the IF circuitry has sufficient bandwidth to accommodate target doppler shifts or else the doppler frequency must be tracked out of the system prior to the IF circuitry - such as by a tuneable local oscillator which is adjusted "closed loop" to center the received IF spectrum at a selected frequency.

In the enclosed embodiments the labeling modulation (ω_m) has been applied by the same unit, e.g. phase shifter **24**, that applies the phase corrections, β_c, however it will be recognized that these two functions need not be mechanized by a single unit. Hence, the phase modulation may be applied by one electronically controllable device and the phase correction to maximize the power on target by another.

For applications involving targets having very slow angular rates, the electrically controllable phase shifters such as element **24**, may comprise conventional piezoelectrically driven reflective mirror type phase shifting devices. One such phase shifter, constructed of a disc shaped piezoelectrically driven bimorph material having a small thin mirror of approximately 5 millimeter diameter, for example, bonded at its center was found to have an extended frequency range before mechanical resonances were bothersome. In applications requiring the phase shifters to have a frequency response above those conveniently obtainable with mechanically or piezoelectrically driven devices, electro-optical phase shifters may be utilized.

In dynamic system applications, a target may be designated to the optical array system at some precisely defined angle and angular rate. Each of the radiating optical aperture elements in the array may have a mechanical steering mechanism (not shown) capable of its own autonomous search, acquisition and track functions. If boresight accuracy is sufficiently high the preliminary search may be performed by only one or two of the radiating channels. After all the elements have separately acquired the target, and are tracking it, the adaptive control loops may be activated and the adaptive array pattern forming and tracking commenced.

In an alternate embodiment shown in FIG. **6**, the energy from a laser **12** is applied to electronically controllable phase shifters **24***a*, **24***b*, and **24***c* by means of lenses **71** and **73**. The output beams from the phase shifter units are applied by lenses **75** and **77** to a laser power amplifier **79**. The amplified beams from amplifier **79** are transmitted by a single telescope **81**. Each of the beams are phase modulated at separate frequencies W_m and are adaptively controlled, in a manner similar to that explained above relative to FIG. **3**, in response to signals applied to each of the phase shifters from a control electronic unit **83**. Unit **83** includes a receiving channel such as **68** of FIG. **3**, as well as the associated processing devices such as **48**, **50**, **52** and **54** of FIG. **3**. Also for electronic scanning applications the phase scanning control signal may be provided by unit **83** and superimposed on, or time shared with, the signals applied to the phase shifter unit **24**. Although in the interest of clarity of the drawing only a single lead is shown from unit **83**, it is understood that in practice a pair of leads may be coupled between each of the phase shifters and unit **83**. The embodiment of FIG. **6** reduces the number of high power laser sources required and by use of a single transmitting aperture simplifies boresighting and angle tracking problems.

Thus there has been described new and improved adaptive arrays wherein multiple, time varying perturbations, for example, phase dithers, are introduced on transmission. The effects of these perturbations are sensed on reception and employed to control feedback loops which adjust the phasing of the plurality of transmitting channels such that the energy at the target is in phase. Some of the advantages realized by systems incorporating the principles of the subject invention are: phase coherency at the target is directly measured rather than being inferred by multiple receiving channel phase measurements; either noncoherent or coherent detection systems may be employed; receiving optics may be located anywhere, thereby avoiding backscattering and cross-coupling problems; the ensemble reference mechanization provides a fail safe system in the sense that the array functions correctly with the remaining elements in the event of the failure of one or more radiating channels; and the defocusing effects induced by moving targets are substantially reduced.

What is claimed is:

1. The method of transmitting a plurality of beams of optical energy such that the plurality of beams are substantially in phase at a target, said method comprising the steps of:
- providing a plurality of beams of coherent optical energy;
- modulating each said beam at a different frequency by varying the transmission path delay of each of said beams at the modulating frequency of that beam;
- transmitting said plurality of modulated beams at a target;
- receiving a portion of the energy reflected from the target; and
- controlling the mean phase of each of said beams to cause the amplitude modulation components in the received energy, which are at approximately the same frequency as the modulating frequency of that beam, to be nulled.

2. A system for transmitting a plurality of beams of optical energy and for controlling their relative phase so that the beams are substantially in phase at a remotely located target, said system comprising:
- a laser;
- an array of electronically controllable optical phase shifters;
- a laser power amplifier;
- lens means for applying the output beam from said laser through said array of optical phase shifters to said laser power amplifier;
- identifying modulation means for applying modulation drive signals at a different frequency to each of said electronically controllable optical phase shifters, whereby each of the output beams from said phase shifters are phase modulated at different modulation frequencies;
- telescope means for transmitting the output beams from said laser power amplifier towards the target;
- receiving means for receiving a portion of the transmitted energy reflected from the target; and
- control means responsive to modulation signal components in the received energy for controlling the mean phase of each of said electronically controllable optical phase shifters so as to null the modulation signal components in the received energy which are at the frequency of the modulation drive signal applied to the respective optical phase shifter;

whereby the phase of said plurality of beams is adaptively controlled so that said beams are substantially in phase at the target.

3. The system of claim 2 wherein said identifying modulation means including a different reference oscillator for supplying the modulation drive signal to each of said electronically controllable optical phase shifters; and said control means including a plurality of control circuits, with each control circuit coupled for controlling the phase of a different one of said beams and comprising a filter having a passband centered at the frequency of the modulation drive signal of the associated beam, and means for applying amplitude modulation signal components of the received energy to said filter, a phase sensitive detector having a signal input coupled to the output of the filter of that control circuit, a reference input coupled to the output of the reference oscillator which supplies the modulation drive signal for the associated beam, and an output coupled to the electronically controllable optical phase shifter disposed in the transmission path of the associated beam.

4. The system of claim 3 wherein each of said electronically controllable phase shifters is a piezoelectrically driven mirror electrically coupled to the associated reference oscillator for applying phase modulation, and is electrically coupled to the output of the associated phase detector for adjusting the mean phase value of said beam.

5. The device of claim 3 wherein each said phase shifters is an electro-optical device electrically coupled to said reference oscillator of the associated beam for providing phase modulation of said beam, and is electrically coupled to the output of said phase detector for correcting the mean phase value of said associated beam.

6. The system of claim 2 wherein said receiving means comprises a plurality of receiving circuits; means for sensing a phase difference between signals in said plurality of receiving circuits; and means for adjusting the phase delay within said plurality of circuits to null the phase difference.

7. The system of claim 3 wherein said receiving means comprises a plurality of receiving circuits; means for sensing a phase difference between signals in said plurality of receiving circuits; and means for adjusting the phase delay within said plurality of circuits to null the phase difference.

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