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George C. Marshall
Space Flight Center
Huntsville, Alabama

ELECTRONIC SCANNING AND BEAM SHAPING METHODS

by

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Project Director

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ABSTRACT

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The results of a study of the current literature concerned with electronic scanning of antenna arrays are presented.

The present state of the various methods of beam scanning is discussed, and the advantages and limitations of each method for particular applications are outlined.

Areas are pointed out in which additional studies are needed.

author

I. INTRODUCTION

Throughout most of the history of radio communications, a radiating antenna has been treated as a passive device which directs the radiated energy into desired but fixed directions. Similarly, a receiving antenna has been treated as a passive device which receives the energy from fixed desired directions. These passive antennas, and particularly arrays of passive antennas, have some inherent performance limitations insofar as their directivity properties, gains, and usable bandwidths are concerned, depending on the orientation, size, and shape of the antenna structure. For example, it is difficult to maintain the high gain of a passive receiving antenna in an arbitrarily unpredictable direction of a moving source since no preprogrammed scanning technique can be used to steer the principal beam. Similarly, it is difficult to increase the gain of a passive receiving antenna arbitrarily and yet maintain a given usable bandwidth. Furthermore, when a passive antenna is used in a satellite or a spacecraft which is not attitude stabilized or which tumbles in space, the signal received by the antenna undergoes a wide variation in amplitude, and in some cases the received signal may become vanishingly small, jeopardizing the communications between the ground station and the spacecraft.[1]

At present, the maximum gain which can be consistently obtained with fully steerable high-gain antennas appears to be on the order of 70 db. This limitation has been primarily due to the inability to construct and maintain extremely accurate large parabolic reflecting surfaces. It also appears that if this limitation were overcome, there may be another limitation on performance due to atmospheric distortion of the wavefront over the relatively large aperture. The requirements for high gain receiving systems for use in receiving communications from deep space probes, however, continue to increase as the complexity and range of these probes increase.[2] Some of these antenna-performance limitations can be avoided by the use of electronically scanned array antennas.

The field of electronically scanned array antennas can be divided into the areas of self-scanning arrays and programmed scanning arrays. This classification is based on the method utilized in controlling the beam pointing parameters of the array. The self-scanning array automatically adjusts these parameters to achieve maximum directivity in the direction of a transmitting source. No information is provided by the self-scanning array to indicate the direction to the transmitting source; however, this produces no limitation as far as communications are concerned. The self-scanning array is capable of providing two way communications with maximum directivity (limited by the array configuration) for both receiving and transmitting to the other station. The programmed-scanning array can be directed to search a predetermined sector of space or maintain a simultaneous search of the sector and provide maximum array directivity to any discovered transmitting source within the sector. Two way communication is possible with the programmed-scanning array maintaining maximum transmit-receive directivity. Information can be made available concerning the bearing to the transmitting source relative to the scanned array. Fig. 1 is a block diagram showing the location of the individual array methods in the overall scheme of electronically scanned arrays. The individual techniques, their advantages and limitations, will be discussed in the succeeding sections of this report.

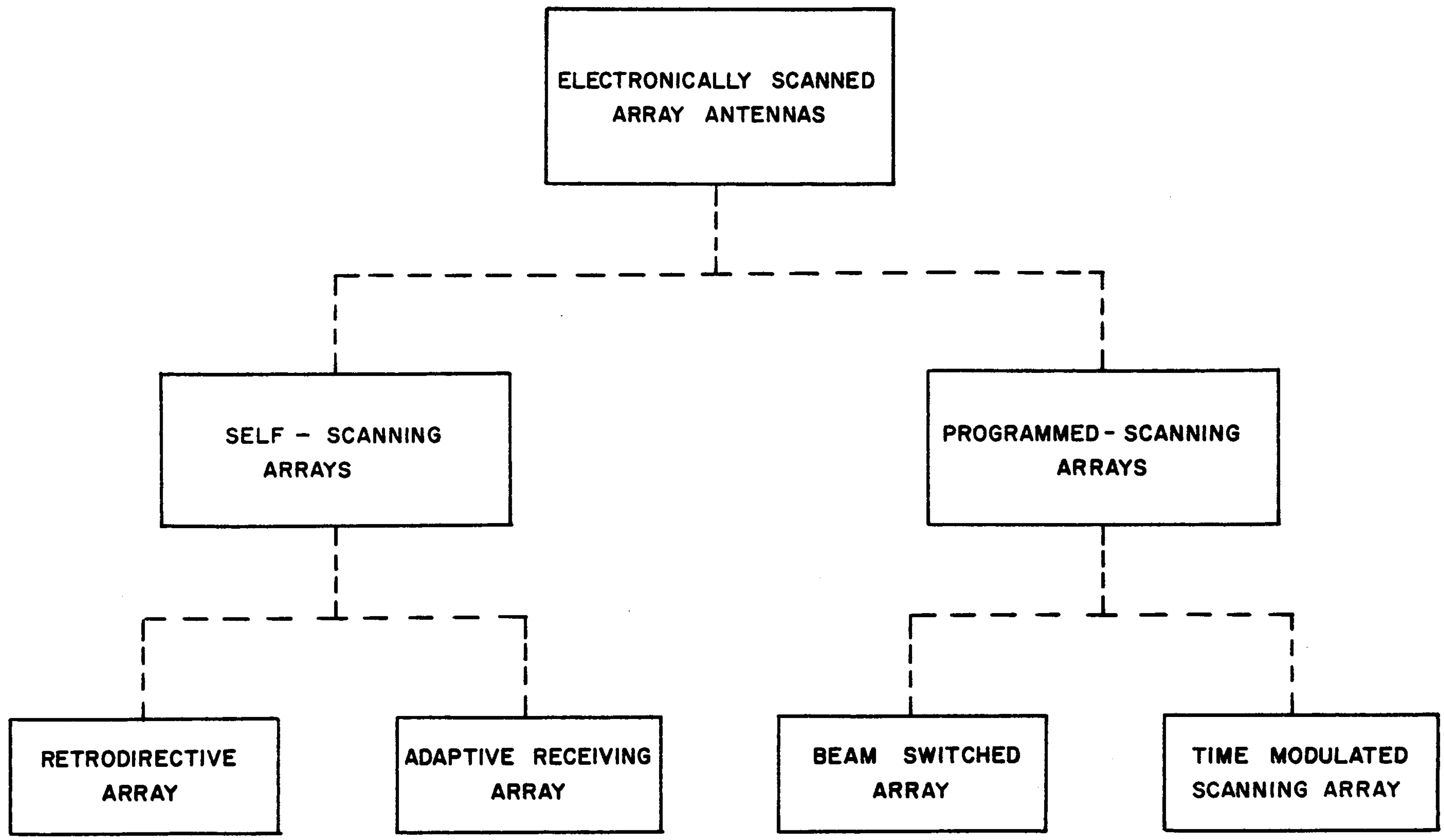


Fig. 1. Block diagram breakdown of electronically scanned array antenna techniques.

2. SELF SCANNING ARRAY

The advantages of high-gain or highly directive antenna systems are well known. There are three ways that such antenna systems have been implemented: 1) reflector-type antennas, 2) lens-type antennas, and 3) array antennas.

2.1 Basic Concepts

The conventional array antenna consists of a number of individual radiating elements suitably spaced with respect to one another. The relative amplitude and phase of the signals applied to each of the elements are controlled to obtain the desired radiation pattern from the combined action of all the elements. The radiating elements might be dipoles, waveguide horns, polyrods, slots, or any other type of antenna. An array consists of more than one element with the maximum number limited by practical considerations. The array antenna differs in concept from both the lens and the reflector. The lens and the reflector apply the proper phase relations to the wavefront after it has been radiated by the source. In the array antenna, the proper phase relationships are applied to the signal before it is radiated, that is, in the transmission lines feeding the individual elements. It is this property of the array antenna that enables electronic control of the far-field radiation pattern.

The self-scanning array, through various electronic means, performs one of two basic operations. The system may sense the phase information available from the incident wavefront and apply this information so as to retransmit a wavefront in such a manner that all the individual contributions are in phase on arrival back at the source, or it may employ an automatic phase-adjusting mechanism in each antenna element such that the signals received by all the elements are added coherently. The first operation defines an approach characteristic of retrodirective arrays. The second operation indicates the process required for an adaptive receiving array.

2.2 The Retrodirective Array

2.21 Principle of Operation

A retrodirective array senses the phase information incident across its aperture and uses this information to transmit a signal that will be coherent on arrival at the source. Fig. 2 illustrates the basic operation of the retrodirective array. A source S, which might be a communications transmitter, radiates a signal that is received at the array. The aperture of the array is divided into smaller subapertures which process the incident signal by performing the phase conjugate operation. If the phase and amplitude of the signal received at the i^{th} subaperture are represented as $|A|\ e^{j(\omega t\ +\ \phi_i)}$, where $|A|$ is the amplitude and ϕ_i is the phase angle with respect to some reference, the signal retransmitted from each subaperture is the conjugate $|A|\ e^{j(\omega t\ -\ \phi_i)}$. It can be shown that when the retransmitted signal is the conjugate of the received signal the contributions retransmitted from each subaperture add coherently at the source to give maximum intensity.[3]

The basic principle of the retrodirective array antenna can be explained by considering the operation of one of the subapertures. Fig. 3 shows a single subaperture with an idealized phase conjugate network. The source at the top of the figure is assumed to be stationary and radiating

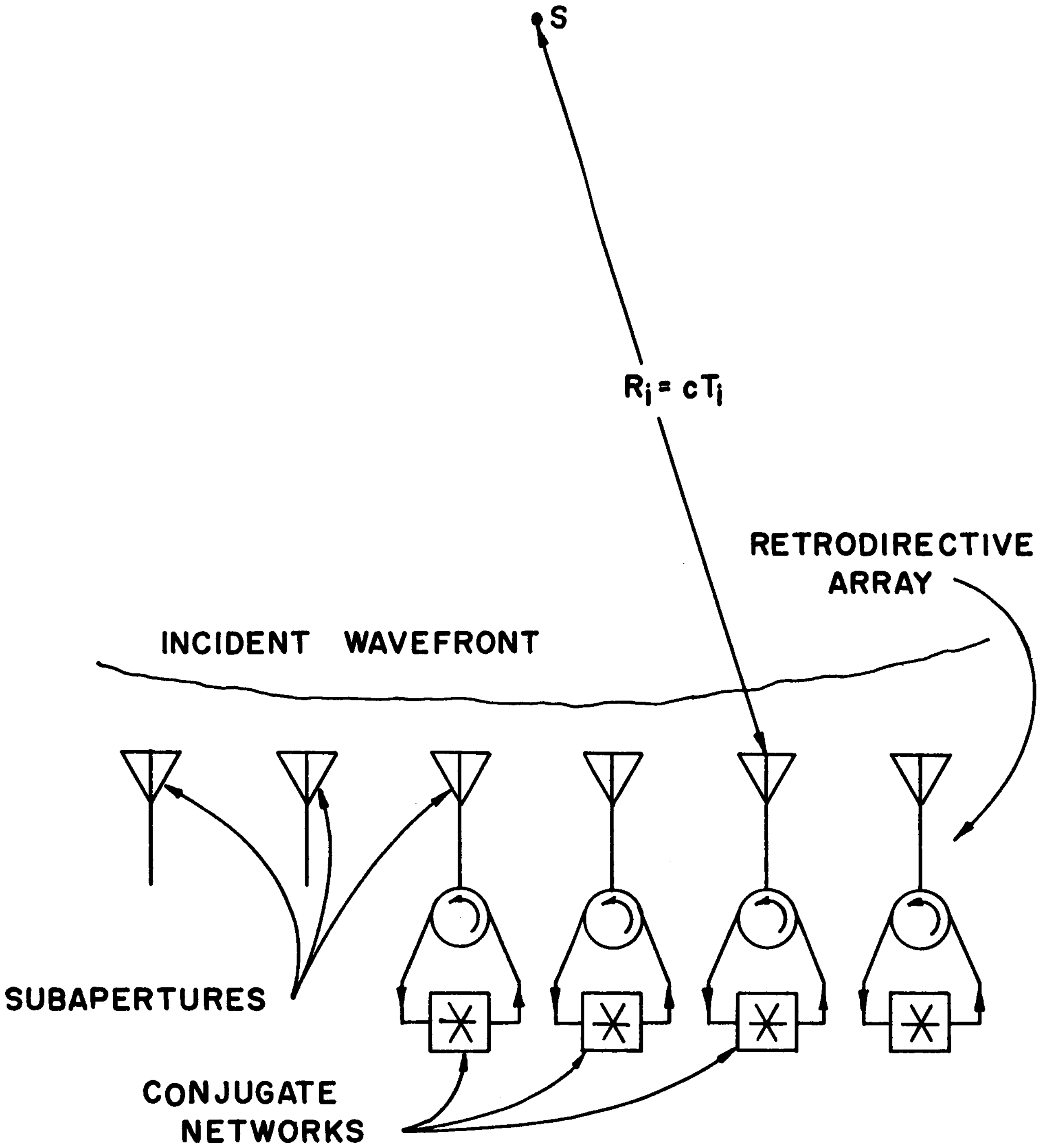


Fig. 2. Irregular wavefront incident on the subapertures of a retrodirective array.

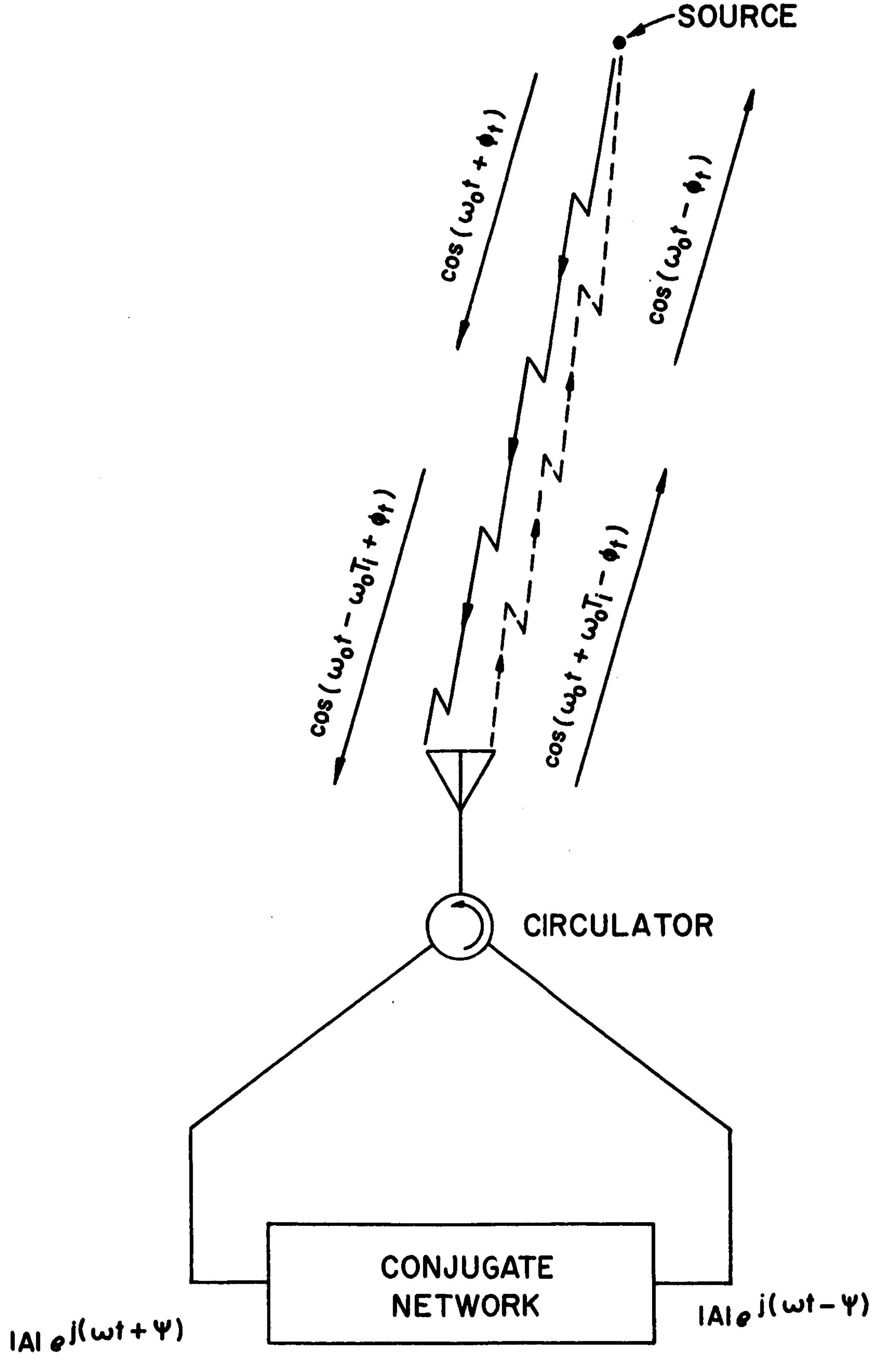


Fig. 3. A subaperture of the retrodirective array.

a signal of the form

$$A \cos(\omega_0 t + \phi_t) \qquad (1)$$

where A is the amplitude, ω_0 is the frequency, and ϕ_t is the phase. At one of the subapertures (the i^{th} one), the received signal is the same as that radiated from the source T_i seconds earlier, where $T_i = \frac{R_i}{C_i}$ is the transit time from the source to the i^{th} subaperture, R_i is the distance and C_i the velocity of propagation along the path. The transit times from the source to the individual subapertures will be different when the path lengths and velocity of propagation differ for the various paths. The signal received at the i^{th} subaperture can be written as

$$A_i \cos\left[\omega_0(t - T_i) + \phi_t\right] \qquad (2)$$

where A_i will be considered unity for all expressions that follow. A circulator is used to direct the received signal to the phase conjugate network and then back to the subaperture for retransmission. The conjugate signal radiated by the i^{th} subaperture is

$$\cos\left[\omega_0(t + T_i) - \phi_t\right] . \qquad (3)$$

On arriving back at the source, the received signal is the same as the signal radiated (3) from the subaperture except for an additional time delay T_i. The signal that arrives back at the source is of the form

$$\cos\left[\omega_0(t + T_i) - \omega_0 T_i - \phi_t\right] = \cos(\omega_0 t - \phi_t). \qquad (4)$$

The argument of the cosine function of the returned signal is the same as that originally radiated by the source (1) except that the sign of ϕ_t is reversed.

Equation (4) points out that the signal radiated by the subaperture is independent of the transit time T_i when it arrives back at the source. Thus the signals from the individual subapertures have the same phase and frequency no matter what the individual transit times might be. The resultant signal therefore is the coherent addition of the signal components from each subaperture. The previous discussion is based on the assumption that the transit time from the source to the subaperture is the same as the transit time from the subaperture back to the source. This assumption requires that the propagation medium be reciprocal and that the medium does not change its character during the time required for round trip transit of the critical part of the propagation path.

The subapertures that make-up the retrodirective array need not be of the same size and their spacing need not be equal. They can be arranged in almost any configuration and can be located on a curved or irregular (excluding the Van Atta array) surface as well as a plane surface. Subapertures may consist of the individual elements of an array, groups of array elements acting in unison, or large aperture antennas such as parabolic reflectors or lenses. The propagation medium across the entire retrodirective array aperture need not be homogeneous, but the medium across any one subaperture must be relatively uniform. Another factor that might enter into the selection of the subaperture size and their spacing is the appearance of large spurious side lobes of grating lobes, especially if the antenna must operate over a wide angle.[3]

The principle of phase conjugation and its role in the retrodirective array has been discussed. In practice the phase conjugate operation can be accomplished in two ways: by using the heterodyning technique, and by using the Van Atta array.

2.22 Phase Conjugation by Heterodyning

The heterodyning technique exploits the phenomenon that when two frequencies are mixed together, the lower sideband contains a phase term which is the conjugate of the phase term in the lower frequency signal. An example of a network that performs the phase conjugate operation is shown in Fig. 4. It is a heterodyning system that consists of two mixers, an IF amplifier and the necessary reference signals. The circulator separates the incoming from the outgoing signals. Mixer No. 1 heterodynes the input

$$A_i \cos\left[\omega_0(t - T_i) + \phi_t\right] \tag{5}$$

with a reference signal of the form

$$\cos\left[(\omega_0 + \omega_{IF})t + \phi_0 + \phi_{IF}\right] . \tag{6}$$

This reference signal is generated by taking the sum signal formed from heterodyning the frequency ω_0 at a phase angle ϕ_0 with the frequency ω_{IF} at a phase ϕ_{IF}, as shown in the box at the bottom of Fig. 4. The reference frequency to Mixer No. 1 must be higher than the received signal frequency in order that the sign of the received signal phase be reversed as required for the conjugate operation. Each subaperture is supplied the same pair of reference signals. The difference frequency or IF signal from the mixer is

$$\cos\left(\omega_{IF}t + \omega_0 T_i - \phi_t + \phi_0 + \phi_{IF}\right) . \tag{7}$$

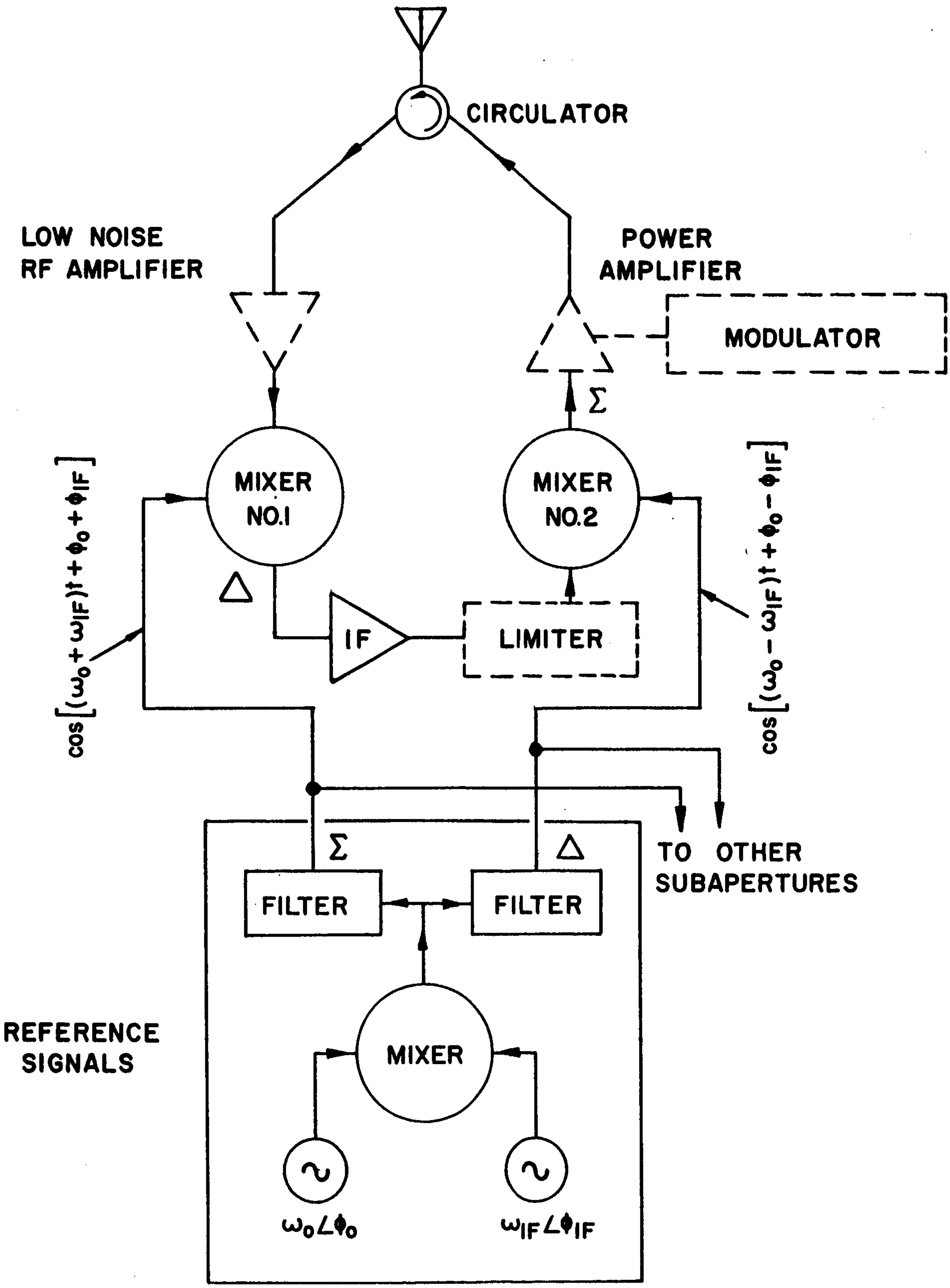


Fig. 4. A subaperture employing the heterodyning method to produce phase-conjugation.

The phase term $\omega_0 T_i$ is reversed in sign by this process. To convert the IF to an RF signal, the second mixer is provided with the reference signal

$$\cos\left[(\omega_0 - \omega_{IF})t + \phi_0 - \phi_{IF}\right] \quad (8)$$

which is also generated as shown within the box at the bottom of Fig. 4. The sum frequency signal is selected from Mixer No. 2 and is

$$\cos\left[\omega_0 t + \omega_0 T_i - \phi_t + 2\phi_0\right] . \quad (9)$$

Except for the phase term $2\phi_0$, (9) is identical with the conjugate signal as given by (3).

The dashed boxes in Fig. 4 illustrate some of the components that may be included in a self-phasing array subaperture but which are not an essential part of the phase conjugate operation. It should be noted that the reference signals are derived from an oscillator at frequency ω_0, equal to that of the distant source. It is necessary in performing the phase conjugate operation that the source frequency ω_0 be known or else measured. Some difference between the reference oscillator frequency ω_0 and the source signal can be tolerated, but too large a difference will degrade the system performance.[3]

The heterodyne technique as illustrated by Fig. 4 is but one method for performing the phase conjugate operation. In principle, it is possible to use a single mixer to perform the conjugate operation if the reference signal is twice the frequency of the input signal. This method requires a microwave mixer which is different from the conventional mixers as discussed in Fig. 4.

C. C. Cutler[9] has proposed a retrodirective array using the heterodyning technique that makes possible large antenna gain even for nonoriented spacecraft. A large number of low-power elemental repeater amplifiers with inputs and outputs connected to like elements in similar arrays, or diplexed on to common elements in a single array are used. The scheme is particularly suited for use with solid-state devices since the low power output of many units is effectively added in phase. Reliability is provided by the many parallel paths through the repeater; failure of individual units will only slightly degrade performance.

A retrodirective array technique for curved arrays is described in an article by E. M. Rutz.[10] A spherical array employing this technique can function as an active repeater in a space telemetry or communication system. In the array the incident wave will be amplified, translated in frequency, and modulated. The phase relation required for reradiation in the direction of the incident wave is obtained in a frequency-conversion process. A microwave tunnel-diode converter has been developed to produce the frequency-conversion operation.[11] A retrodirective array using a single microwave mixer to accomplish conjugate phase shift in each element is described by C. Y. Pon.[12] Reradiation patterns were measured for a four-element array using the mixer. The patterns compare favorably with those predicted by conventional array theory.

2.23 The Van Atta Array

The Van Atta (VA) array performs the conjugate operation required for retrodirectivity by simple interconnections of the array elements. It can operate as a passive retrodirective antenna or as an active device by inserting amplifiers in the transmission lines, provided they can amplify in either direction.

The principle of operation of the array can be better understood by referring to Fig. 5 where the layout of a four-element one-dimensional passive array is depicted. The elements located equidistant from the center of the array are connected with a low-loss transmission line. The lines connecting such pairs of elements are the same electrical length. For a plane wave incident at an arbitrary angle θ, the signals collected by the elements will have an interelement phase delay (left to right) of B radians, where $B = \frac{2\pi D}{\lambda} \sin\theta$ such that the signals collected will have relative phases of 0, -B, -2B and -3B. The collected signals will then travel through the transmission line and be ready for radiation after undergoing an additional but identical phase delay determined by the electrical length of the transmission line. Therefore the relative phases of the radiated signals will be 0, B, 2B and 3B, or precisely the phasing required to form a plane wavefront and hence to transmit in the direction θ[5].

The reflecting principle of the passive VA array is readily extendable to a two-demensional planar array if one connects conjugate pairs of elements with an equal-length transmission line. A two dimensional sixteen-element array would be represented as in Fig. 6. Element pairs are specified in Fig. 6 by the same number. The array can be mechanized in a number of geometries, among which are (in addition to linear and planar) circular, cylindrical, and spherical.[6,7]

The development has shown that retransmission will take place in the direction of reception, however, it does not show what happens in other directions. This can easily be calculated from conventional array theory, since, for transmission, the aperture can be seen to consist of an array

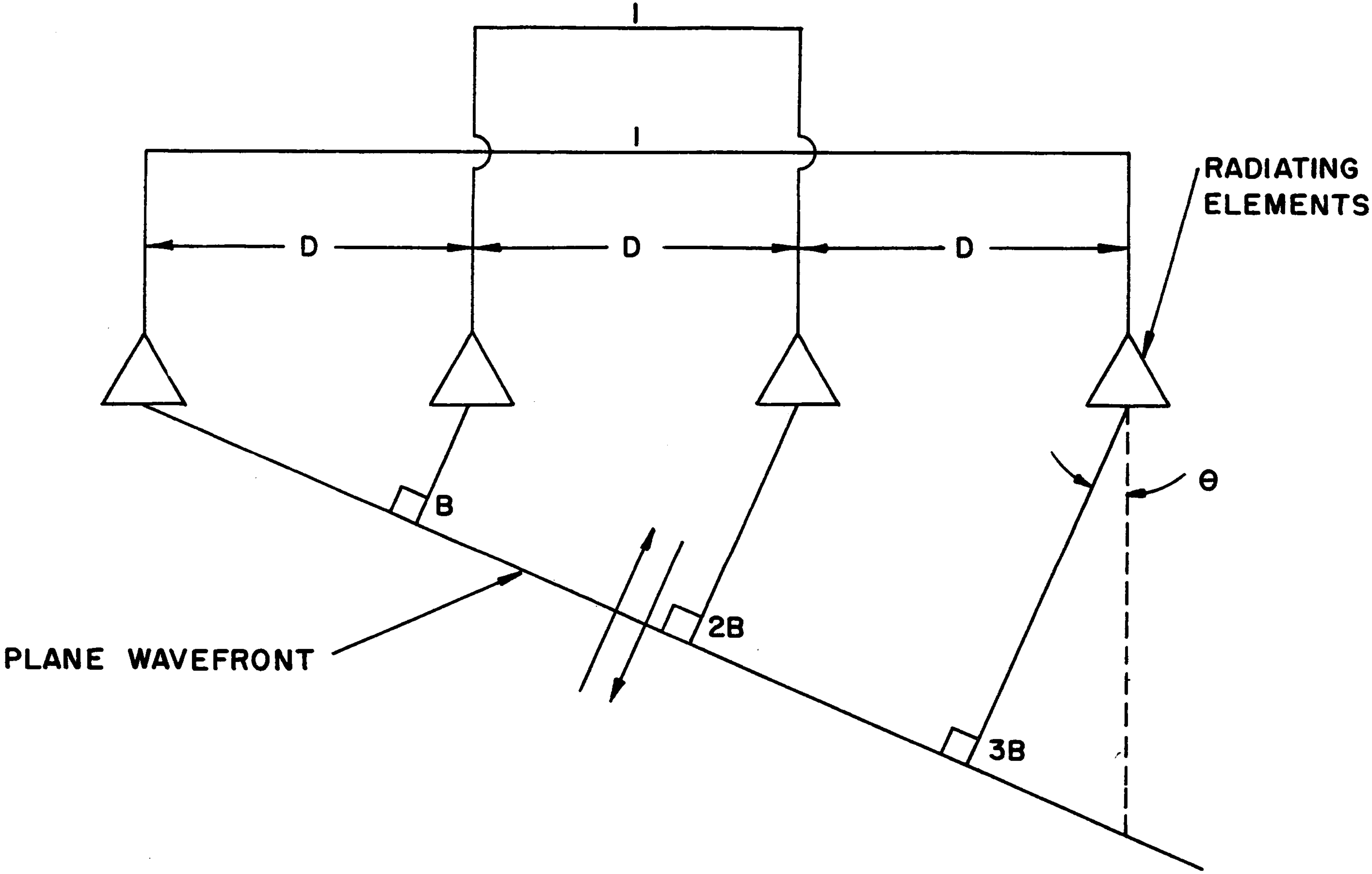


Fig. 5. Four-element passive Van Atta array.

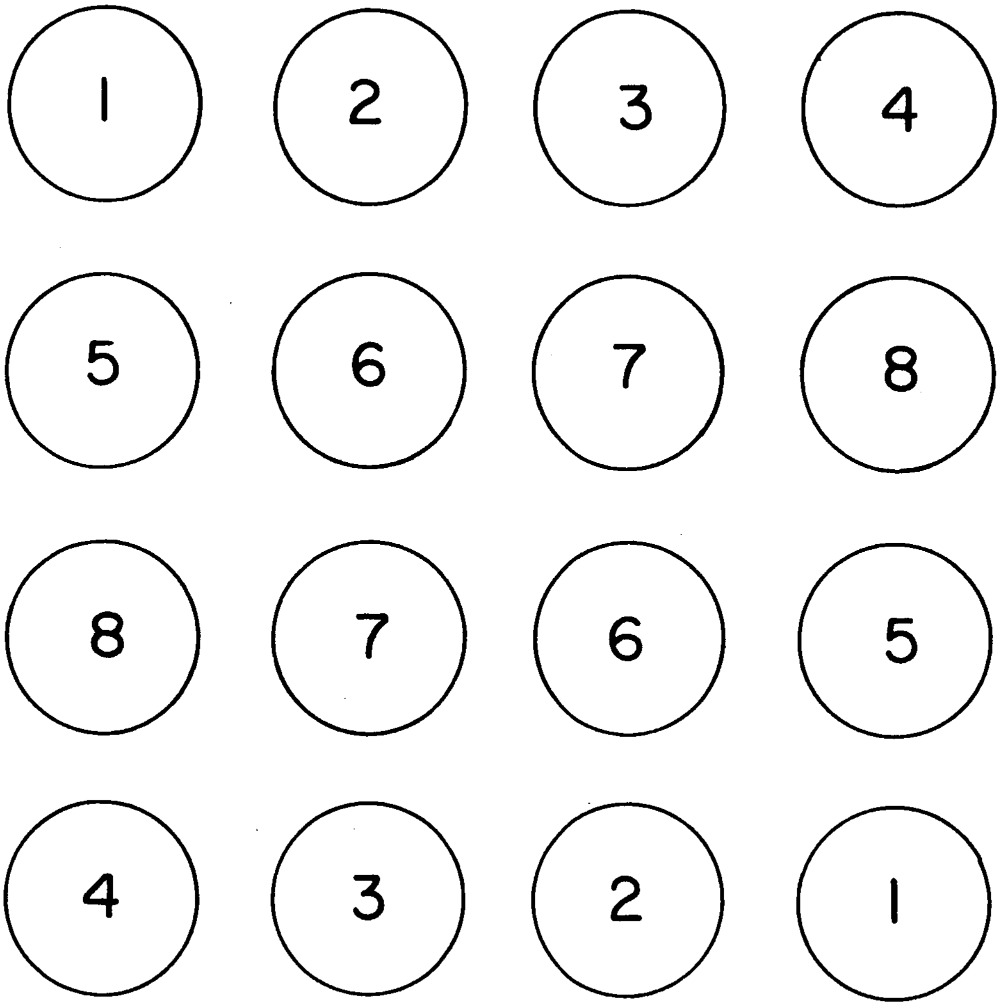


Fig. 6. Sixteen-element Van Atta planar array connection diagram.

with a linear phase shift across the aperture related only to the direction of reception. If the distance between adjacent elements of the array is less than or equal to $\lambda/2$ the majority of the received energy will be returned in the direction of one main lobe of the pattern.

The active VA array requires the use of amplifiers in each transmission line connecting two elements. The amplifiers must exhibit bilateral gain or two back-to-back unilateral amplifiers could be used. Circulators to separate signals in the two directions could be used as shown in Fig. 7.

The fundamental reason for using an active VA array rather than a passive one is to reduce the required aperture of the array for a prescribed incident power density and effective radiated power. The upper limit of amplifier gain is set by the fact that mutual coupling exists between element pairs, producing feedback and the possibility of oscillation. The amount of isolation provided by the circulators (Fig. 7) also limits the loop gain between circulators. Circulators of modest (20-db) isolation which would allow 15 db of gain are readily made in compact printed strip line form. In fact a slot or dipole array could be printed with the circulators built in.[7]

Various techniques can be used to provide isolation between element pairs and thus enable the use of higher gain amplifiers. When two "subarrays", one for receiving and one for transmitting, are used, the retrodirective properties of the single VA array are identically realizable. The two subarrays are interconnected as shown in Fig. 8 for a linear array. Extensions are easily made to planar arrays. In the interconnecting transmission lines, only unilateral amplification is required.

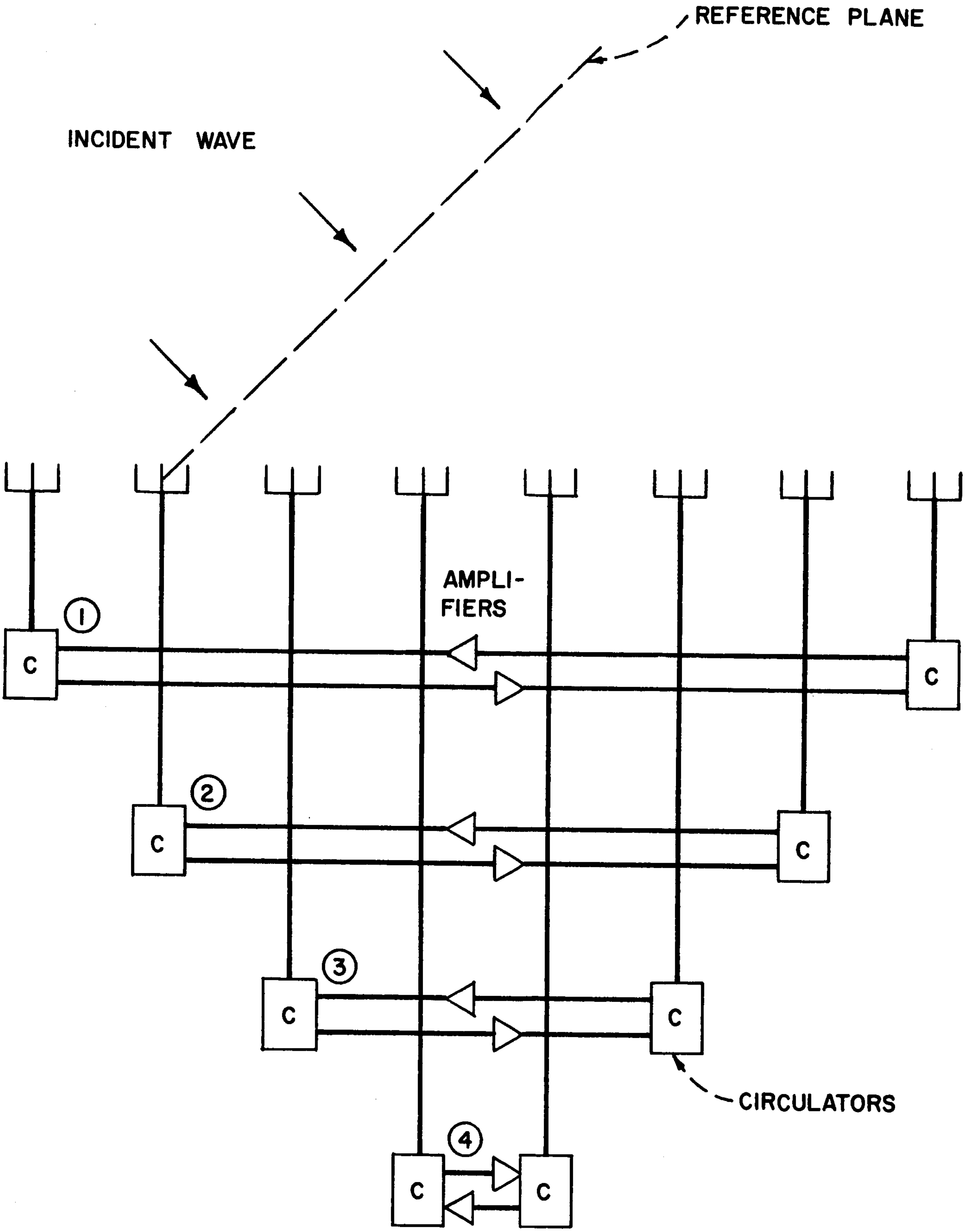


Fig. 7. An active Van Atta array.

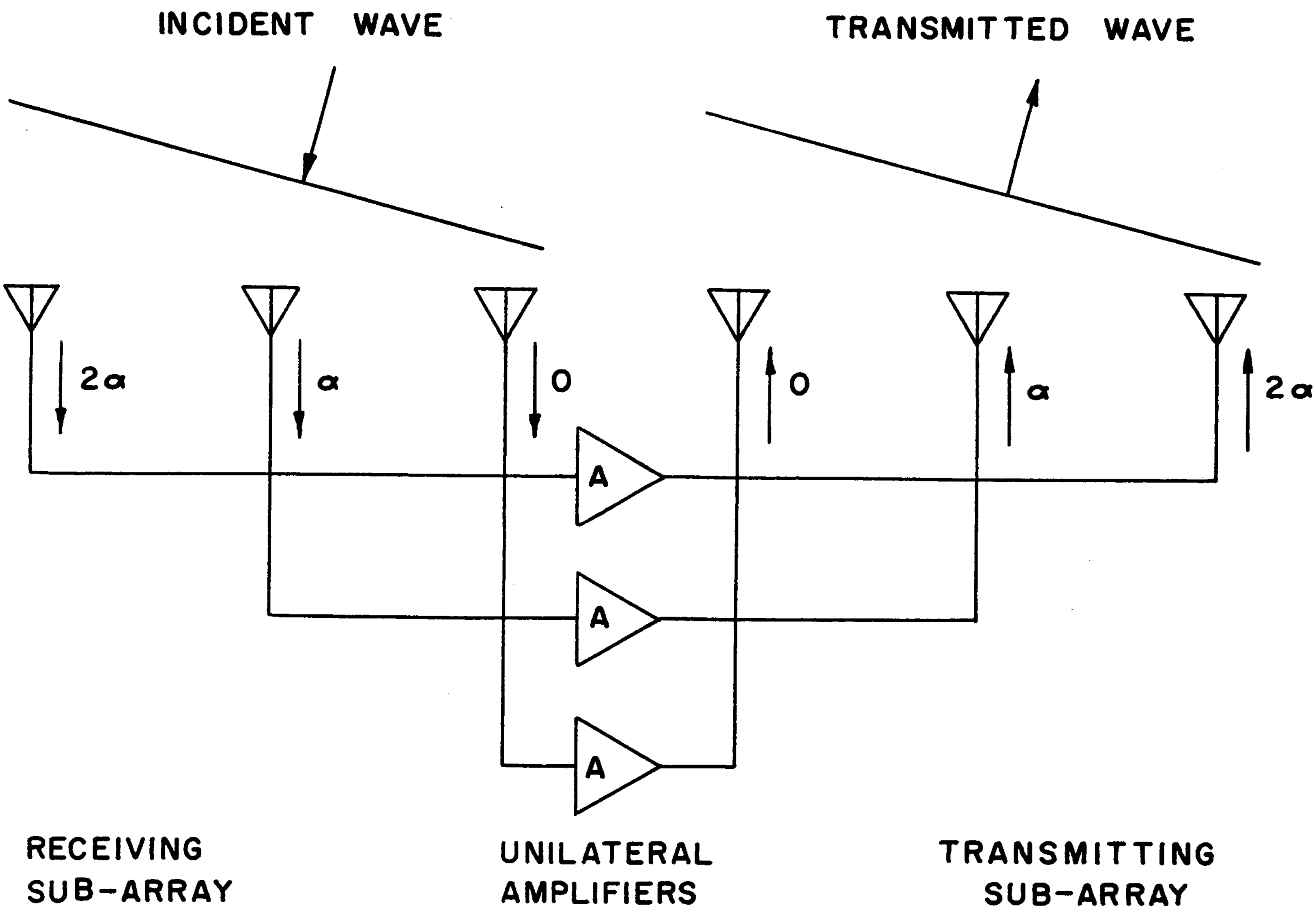


Fig. 8. Active Van Atta array employing two subarrays to provide element isolation.

The separation of the receive and transmit functions allows a flexibility in the choice of polarization and spacing of the two subarrays which can be used to provide isolation. For example, if the two subarrays are physically separated, any degree of isolation can be obtained. This, however, requires twice the aperture of a single array. On the other hand, if the directions or senses of polarization of the receiving and transmitting subarrays are orthogonal, it has been found that the coupling between the two subarrays can be reduced. Using this approach, it is possible to intermesh the two subarrays on a common aperture and obtain a relatively high degree of decoupling. Another method for providing isolation is that of frequency conversion to provide a shift between the transmitted and received frequencies in the array. With the aid of filters, the amplifier isolation can be further increased over that provided by the orthogonal polarization. The local oscillator also serves as a convenient means of modulating the array. The block diagram of Fig. 9 indicates a typical configuration for phase modulating the received carrier.[8]

Another factor which must be considered in an active VA array is the effect of phase errors introduced by the amplifiers on the array gain. A worst case analysis of the effects of phase error in a phased array shows that $\pm$ 30° phase tolerance results in a worst case array gain only 1.2 db below that achieved with no phase error. This degree of accuracy can be obtained with little difficulty. Phase tolerances can also be prescribed to maintain the sidelobe structure below given levels and this results in a tighter phase tolerance.[8,13]

A number of applications of the VA array have been proposed in the literature. A discussion of the possible application of a VA array to a stationary-satellite communications system has been given by Hansen[7],

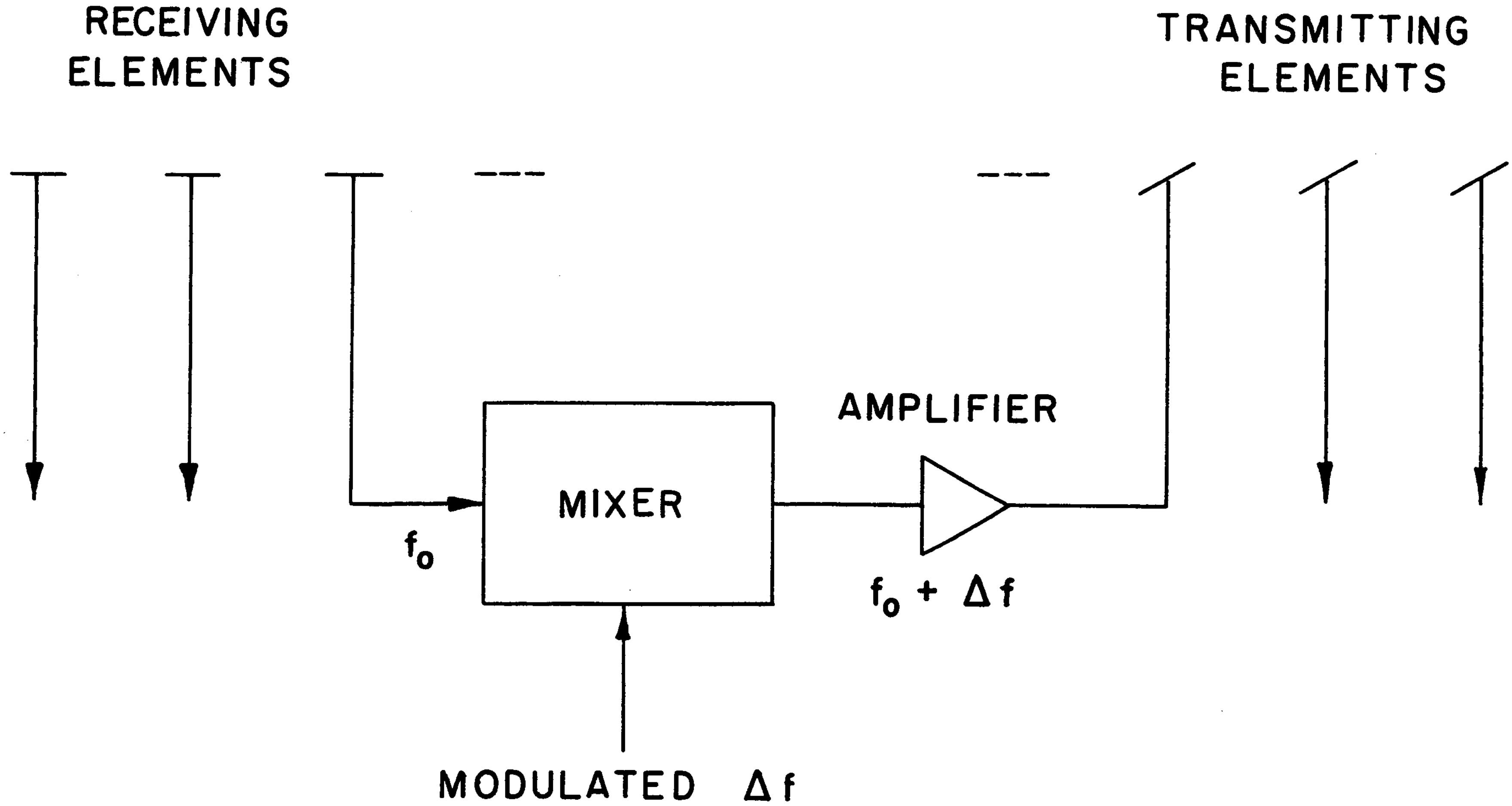


Fig. 9. Active Van Atta array modulation.

who also discusses the high degree of reliability for such systems. Davies[6] proposes that the VA array can be used in several different ways. For one, a telemetry system to provide data from satellites could be realized by radiating unmodulated signals from the ground station, directed at the satellite, and by arranging for this signal to be modulated by the data for retransmission to the ground station along the same path. This technique has also been considered by Gruenberg[5] along with a discussion of various modulation schemes. By the proper location of the array elements or a number of independent arrays on the satellite, it would be possible to provide directive communications without satellite stabilization. The use of tunnel diodes and strip line circuit elements in conjunction with the VA array is discussed by Andre.[8]

2.24 Other Characteristics

Retrodirective arrays can be of value when applied in situations where little information is available concerning the incident wavefront produced by some source. It is required that the system operate with a two-way transmission path, as for instance in point-to-point communication systems. The subaperture configuration is restricted to symmetrical surfaces if the VA technique is used to provide phase conjugation. The energy from each subaperture (if the heterodyning technique is used) when transmitted back to the source will be coherent and therefore will be a maximum no matter what the relative configuration of array elements might be. The relative configuration of elements, however, will determine the form of the sidelobe radiation. The electronic circuitry required for the phase conjugate operation can be fabricated using strip transmission lines and semiconductor devices. This provides compact low power circuitry at a minimum of weight and cost. The primary problem associated with retrodirective arrays is the required isolation between incoming and outgoing portions of the subaperture circuit. The isolation can be improved by providing space separation (two antennas) or by frequency separation and filtering (outgoing frequency different from incoming frequency).

2.3 Adaptive Receiving Array

The primary function of an adaptive receiving array is that of detecting the modulation or information contained in the signals received by the array subapertures with a maximum signal-to-noise ratio. Assuming that the noise in the various subapertures is not coherent and that the signals in the subapertures can be added coherently, a SNR equal to the summation of the subaperture SNR's may be obtained.[16] The coherent addition process can be accomplished by using a phase-lock control system at each subaperture locked to a common reference signal. This in effect steers the main beam of the array automatically to the direction of the signal source. Fig. 10 shows three basic phase-lock control systems for accomplishing coherent signal addition. It can be seen that the three methods differ only in what is used as the phase detector reference.

2.31 Theory of Operation

The principle of operation of the adaptive receiving array can be better explained by considering the performance of any subaperture, say the N^{th} one, and its associated phase-lock control system, Fig. 11. Let the received voltage at the N^{th} subaperture be expressed as

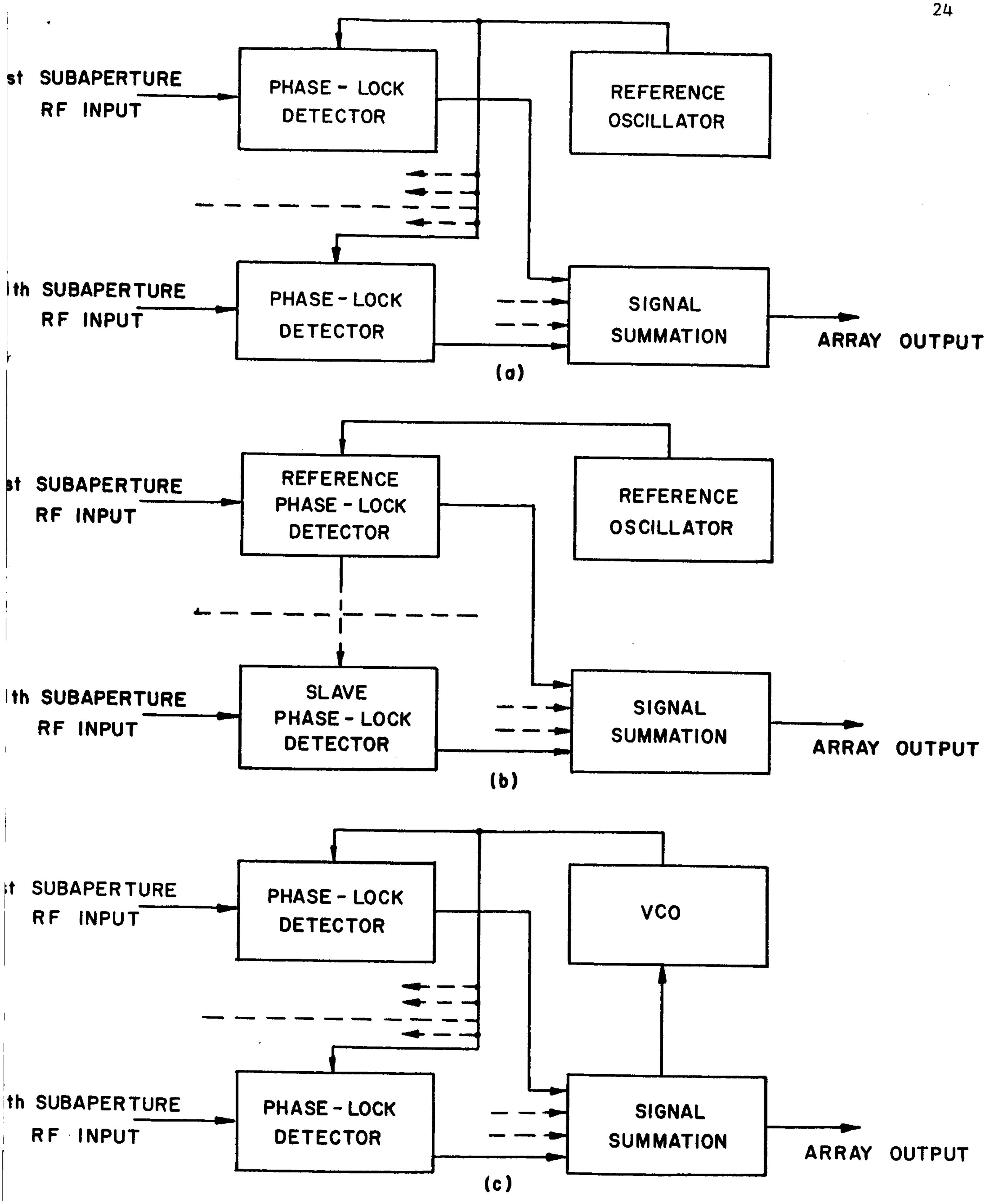


Fig. 10. Basic phase-lock control systems.
(a) Stable oscillator as reference.
(b) Signal channel as reference.
(c) Summation signal as reference.

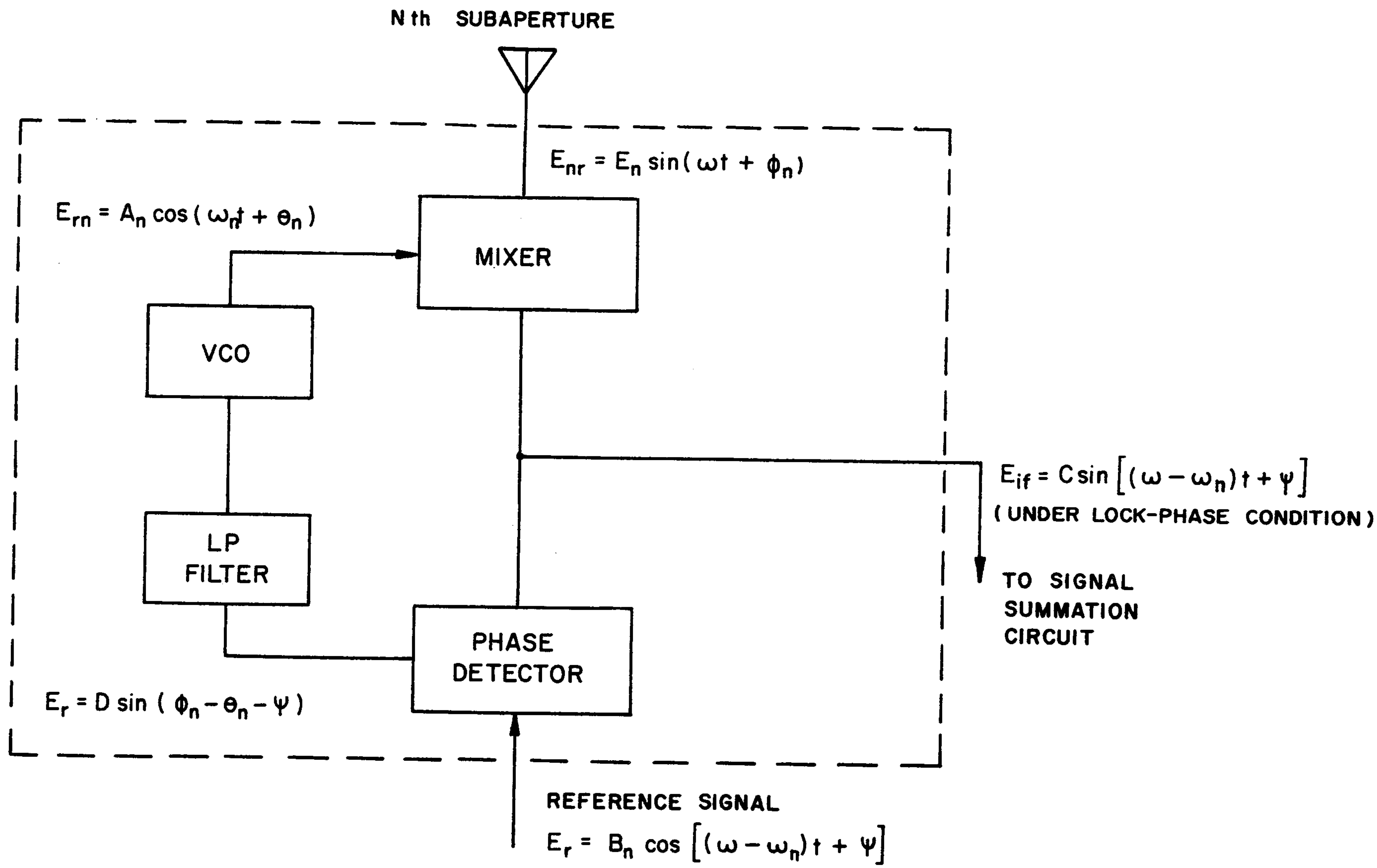


Fig. 11. Phase-lock detector.

$$e_{nr} = E_n \sin(\omega t + \phi_n)$$

where E_n = amplitude of received signal

ω = angular frequency of the received signal

ϕ_n = relative phase angle of the received signal.

To consider the basic operating principle we will assume a noiseless system. With reference to Fig. 11, let the signal output of the voltage-controlled oscillator (vco) be

$$E_{rn} = A_n \cos\left[\omega_n t + \theta_n(t)\right]$$

A_n = amplitude of vco output voltage

ω_n = a constant angular frequency

$\theta_n(t)$ = phase of the vco which is a function of the control voltage.

When the received signal and the signal from the vco are mixed and properly filtered, the output can be expressed as

$$E_n' = k \sin([\omega - \omega_n]\ t + \phi_n - \theta_n)$$

where k is a constant depending on the mixer characteristics. If now the reference signal to the phase detector is of the form

$$E_r = B \cos([\omega - \omega_n]\ t + \psi)$$

the error signal can be expressed as

$$E_e = D \sin(\phi_n - \theta_n - \psi) \qquad (1)$$

where ψ is a phase angle associated with the reference signal and which must be the same for all subapertures. The vco is so designed that $\theta_n(t)$ will be changed until the error signal (1) is zero. This will occur when

$$\theta_n = \phi_n - \psi \, . \tag{2}$$

The subaperture output signal under the conditions of (2) can be expressed as

$$E_{if} = C \sin \left[(\omega - \omega_n) t + \psi\right]$$

which is independent of the relative phase angle (ϕ_n) of the received signal. Under the ideal conditions assumed here it is obvious that the summation circuit of the adaptive receiving array will produce coherent addition of the signals received by the array subapertures.

2.32 Acquisition Time

Since in the adaptive receiving array the phase angles of the signals arriving at the summation circuit are adjusted by the phase-lock control system of the subaperture, there will, in general, be a definite time lag between the time the array starts operating and the time when the phase angles are properly adjusted. This time lag will be due primarily to the time required for various phase-lock loops to lock. The "lock-in" time for each phase-lock loop assembly depends on the loop bandwidth and its input SNR. It will also be a function of the damping constant of the phase-lock loop filter. Thus, the higher the subaperture SNR, the shorter the array acquisition time. From the previous discussion it is seen that the initial detection of the adaptive array is incoherent, and furthermore, the incident wavefront must be stationary (that is, its characteristics do not change) during the time required to adapt. Therefore adaptive receiving arrays have a threshold level that is determined by the threshold of the subaperture phase-lock control system. C. S. Weaver[14] has analyzed thresholds and tracking ranges of typical phase-lock control systems.

Various experimental models of adaptive receiving arrays have been tested and the results published. An adaptive array consisting of four subapertures, utilizing the phase-lock loop control system of Fig. 10(c), has been constructed and evaluated by Schrader.[2] His results are in agreement with the SNR improvement predicted by the theory. Svoboda[15] describes a six-element experimental array that uses the control system of Fig. 10(a) operating on the IF rather than the RF subaperture signal. He includes a discussion of the effects of interference on array performance and methods for minimizing these effects. Other phase-lock control systems have been investigated by Schrader[16], Breese, et.al.[17], and Breese and Sferrazza[18].

2.33 Advantages and Limitations

The adaptive receiving array allows a large receiving aperture to be comprised of smaller subapertures, each of which has only to be pointed with its usual accuracy. In this way, apertures greater than the current single steerable aperture limit of around 300 ft. diameter can be realized. Furthermore, directivity limitations due to manufacturing tolerance or due to tropospheric scintillations can be overcome at least in principle. The array is not restricted to applications that require large apertures, it can be used to advantage where restrictions are imposed on the location of the array subapertures such as airplanes or space vehicles. Along with the several advantages of the adaptive receiving array are limitations produced by the finite acquisition time of the control systems and the problem of reduced effectiveness in the presence of multiple sources.

3. PROGRAMMED SCANNING ARRAYS

3.1 Array Classification

Programmed scanning arrays can be classified according to the technique used for combining the signals from the separate antenna elements into a single coherent array output. If delay lines are used, a delayed array results. If phase shifters are employed, the system is called a phased array. The principal difference between these methods is the variation of carrier phase shift with frequency. A delayed array operates using phase shift that is linear with frequency; in a phased array phase shift is insensitive to frequency changes. Although the first system is more desirable for wide-band signals, it is usually difficult to instrument, and phased arrays are often selected instead. The nature of the device used to produce phase shift or time delay is such that discrete steps can be controlled with greater accuracy than continuous changes. Thus the delayed array and the phased array are usually instrumented to produce discrete beams in space with a switching arrangement selecting the desired beam. The arrays discussed above are classified in general terms as beam switched arrays. Also included in the field of programmed scanning arrays is the time modulated array utilizing periodic modulation of the aperture excitation to produce simultaneous beams pointing in different directions.

3.2 Beam Switched Arrays

3.21 Array Design

The usual method of designing an array is based upon the principle of pattern multiplication: The array pattern is the product of the element pattern and an array factor.[19] In its simplest form, the use of this procedure assumes that the pattern of any element radiating in the presence of the remaining elements in the array and their supporting structures is the same as the pattern of an isolated element. This is never true in practice because of parasitic excitation of adjacent elements and scattering from the supporting structures.[20] However, in a large array almost all radiating elements are in an essentially uniform environment. Hence, a representative element pattern, which is usually quite different from the isolated element pattern, can be determined. Although not valid for those array elements located very close to the edge of the array, this representative pattern, when multiplied by the array factor, still permits acceptably accurate prediction of the array patterns. This is especially true for a tapered illumination.[21]

The design requirements usually specified for a phase-scanned array are the width of the scan sector, the half-power beam width, and the side-lobe level. From these requirements, it is possible to determine the following parameters: element pattern shape, element spacing, and number of radiating elements required. The half-power beam width of the element pattern must be equal to or slightly greater than the scan sector in order to prevent the power gain of the array from decreasing more than 3 db as the beam is scanned away from broadside.[21]

The properties of planar and linear phase-scanned arrays consisting of a large number of equispaced radiators have been studied in detail. In summarizing some pertinent results of a study by Von Aulock[22], it may be said that the introduction of a phase delay across the wavefront radiating from an array has many consequences in addition to the obvious shift of the beam maximum:

1. The beam width increases when the beam is scanned away from broadside.
2. The beam shape changes slightly when the beam is scanned from broadside to moderate scan angles and changes drastically at extreme scan angles.
3. New side lobes may appear at moderate to large scan angles.
4. The beam direction is slightly different from that computed by standard formulas.
5. The beam-pointing error in a phased array is esentially caused by systematic errors in phase delay, whereas moderate random errors in phase delay have relatively little effect on the characteristics of such an array.

3.22 Feed Structure

Once the configuration and the illuminating function of the array have been established, an appropriate feed which will produce the desired illumination function must be designed. This feed system must be suitable for the incorporation of the time-delay or phase-shifting element in order to produce the desired scanning.

Since a planar array of uniformly spaced elements can be considered to consist of a number of linear arrays it will suffice to define possible feed structures for linear arrays. These feed structures utilize traveling wave power distribution or corporate power distribution or a combination of both. If one classifies linear arrays according to their feed structure, one may speak of end-fed arrays utilizing traveling wave distribution, parallel-fed arrays using corporate distribution, and sectioned arrays using both. The feed structures with their associated scanning control element location are shown in Fig. 12.

The choice of a suitable feed structure for any particular application depends on several factors. Some of the more important to be considered are the maximum power to be radiated, the operating frequency, the required band width, and the complexity of the control circuits.

The maximum power handling capability of the array is usually limited by the phase shift or time delay device. Clearly, with this limitation in mind, the parallel-fed array can be operated at the highest peak-power, and the total power-handling capability of the array is proportional to its aperture.

Strip transmission line techniques can be used to build compact corporate feed devices that will operate effectively at frequencies below 3 Gc. At frequencies much above 3 Gc the stripline dimensions become small thus increasing the phase and amplitude error introduced by the feed structure. The size of a corporate feed constructed from waveguide components becomes large for an array of many elements. Thus the application of compact parallel-fed arrays is substantially limited to frequencies below 3 Gc using stripline techniques. Above 3 Gc the use of series-fed and sectioned arrays become attractive. The sectioned array is a combination of end-fed and parallel-fed arrays and is useful when an antenna of very large aperture is required.

The control circuitry required to scan the array is relatively simple for end-fed arrays and sectioned arrays, whereas it may be quite complicated for parallel-fed arrays with large apertures because each individual controlled element requires separate programming. By incorporating symmetrical properties of the basic feed structures in the

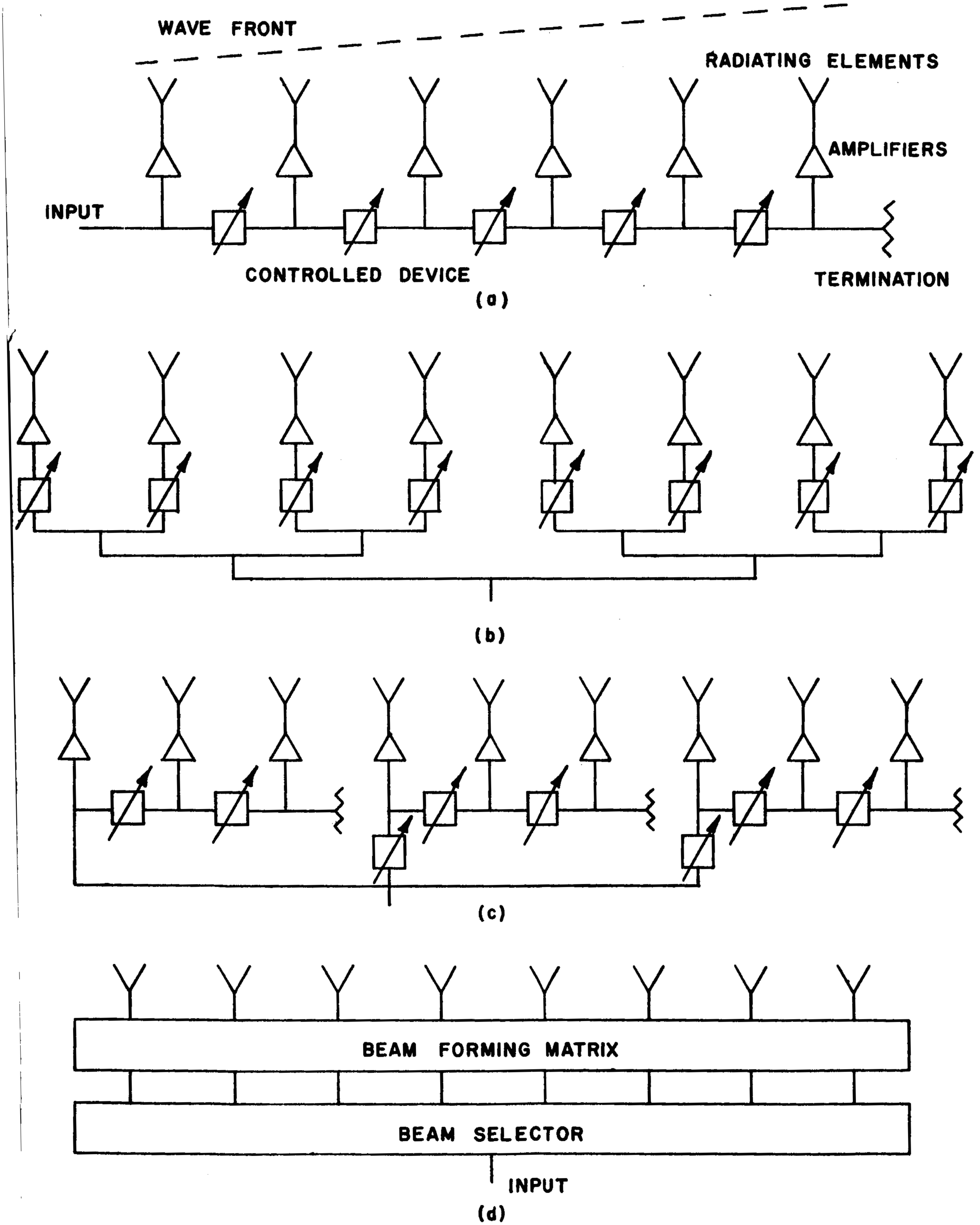


Fig. 12. Linear Array Feed Structures.

(a) End - Fed Array.

(b) Parallel - Fed Array.

(c) Sectioned Array.

(d) Beam – Forming Matrix A

array design it is possible to reduce the number of components in the electronic control circuit. If the controlled element settings in a symmetrically fed array are interchanged with their counterparts in the opposite half of the array, the beam will scan through a sector which is the mirror image of the original sector. Two feed structures are applicable to this scanning method: the parallel-fed structure, and a center-fed traveling wave feed (Fig. 13).

The operating bandwidth of the array also imposes certain restrictions on the choice of a suitable feed structure. It is obvious that corporate power distribution enables broadband operation, however as pointed out above it can be relatively bulky. On the other hand, the traveling wave distribution is compact, but is very sensitive to frequency change.

Another feed structure, the beam forming matrix, utilizes corporate power distribution and fixed phase shifters. Beam scanning is accomplished by selecting the desired input port corresponding to a fixed beam direction. This technique will be discussed in a later section of the report.

3.23 The Controlled Element

The operation of a beam-switched array depends upon the ability to control electronically the phase or time delay introduced in the feed system. If one attempts to control electronically one or more of the transmission line parameters to change the phase constant (β) of a section of line to effect a change in electrical line length (Fig. 14a) the characteristic impedance is also generally changed. This creates an undesirable mismatch. However, if sections of such lines are

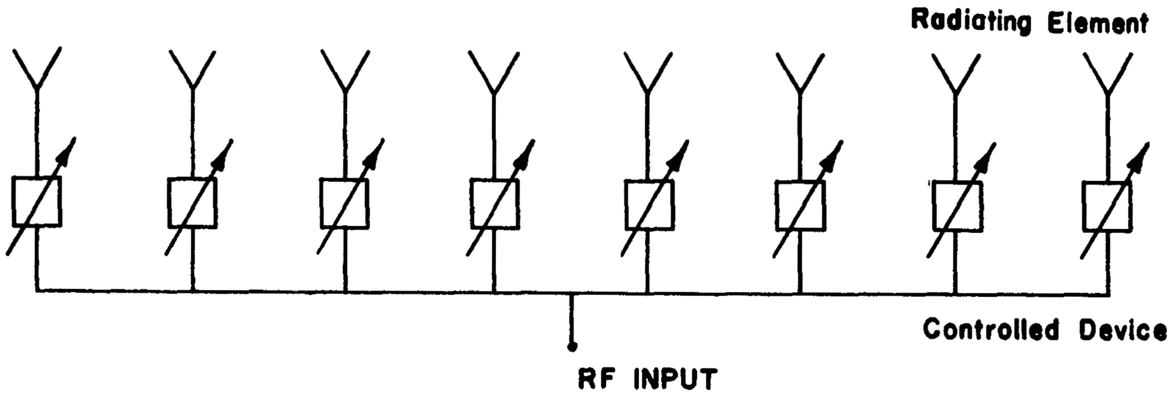


Fig. 13. Center-fed traveling wave structure.

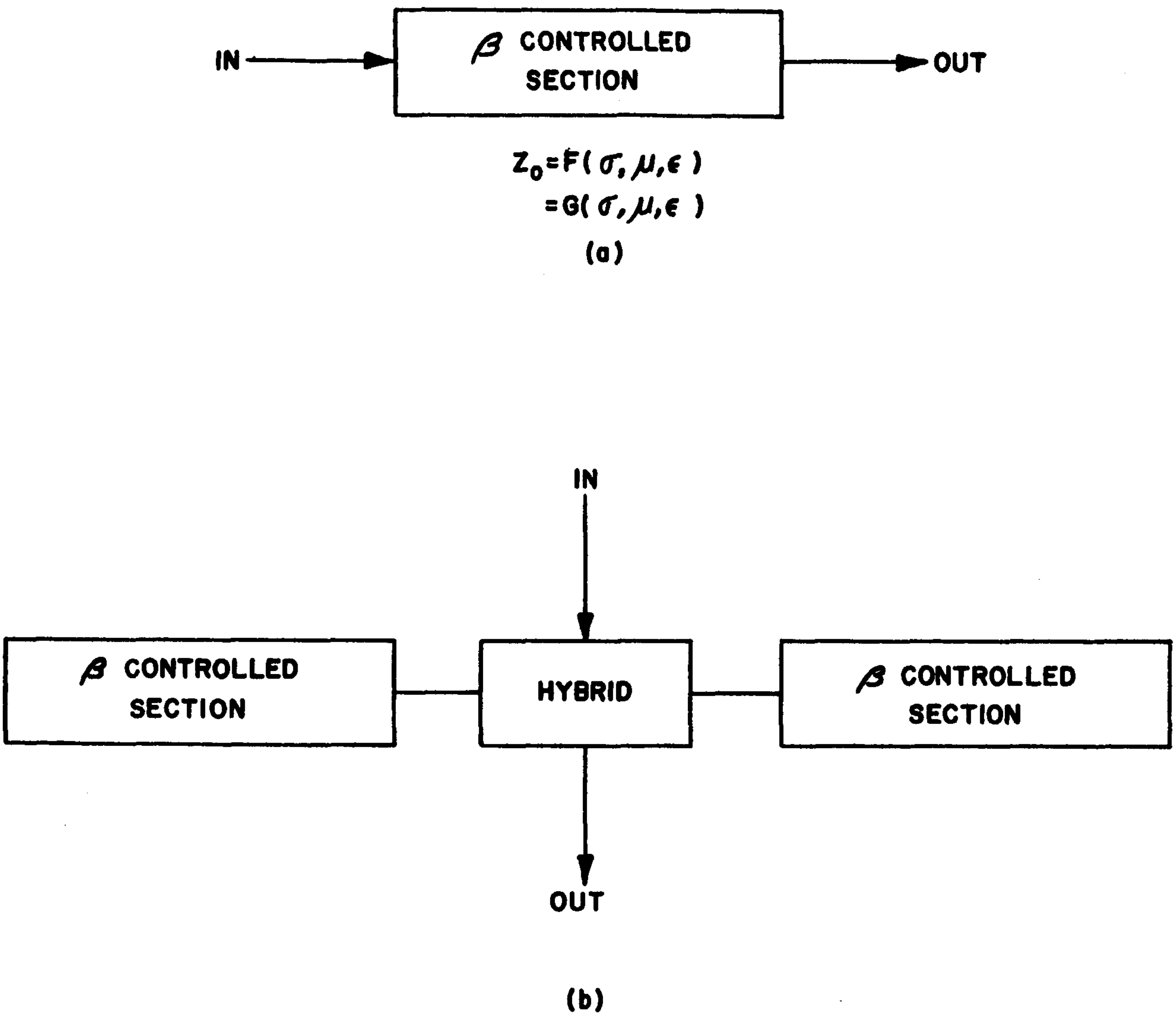


Fig. 14. Controlled device configuration.
(a) straight-through structure
(b) balanced structure

appropriately used (Fig. 14b) as arms on a balanced structure such as a hybrid, a net change in electrical line length results without input and output mismatches. The design problem now becomes that of designing low loss electronically variable β sections of transmission line. There are many types and variants. Some nonlinear material properties may not readily be utilized to provide the 360 degrees of phase shift or time delay that is desired in one β control section. Thus, cascading hybrids rather than control sections in one arm may be desirable.[23] β controlled sections have been constructed using ferrites, traveling wave tubes, gas devices, and diodes.

The discovery of ferromagnetic semiconducting materials, such as ferrites, which are transparent to and interact with microwaves, made it possible to develop a whole family of novel microwave devices. In particular, it was shown as early as 1952 that ferrite-loaded waveguides inserted into an external biasing magnetic field could be used as electrically-controlled phase shifters. Early experiments indicated that there exists a threshold peak-power level at which ferrite loss increases sharply with peak-power. It was also discovered that a pulse propagated through a ferrite-loaded waveguide may undergo a distinct change in shape. This pulse deterioration depends on pulse length, applied peak-power, and d-c magnetization. In achieving a practical ferrite phase-shifter a compromise is needed between phase-shifting ability and high-power-handling capability. A similar compromise is needed with respect to the insertion loss of the phase shifter. Whereas low-loss ferrites are most desirable for the development of a low-loss phase shifter, these materials become nonlinear above a certain relatively low threshold power and exhibit an insertion loss of many decibels. Lossy ferrites have a much higher threshold power at which they become nonlinear but may produce an undesirable high power dissipation in the phase shifter at all levels of operating power.[21] A phase shifter (of the form of Fig. 14a) for an X band phase scanned array was developed by Bell Labs.[21] that could handle 15 kw of peak-power without deterioration of performance and could produce a maximum useful phase shift of 90° per inch.

In mechanically-scanned antennas the inertia of the moving part places an upper limit on the scan rates and rates-of-change of the scan rates which can be achieved. In addition, the power requirements for operating the mechanical scanners are relatively large. Similar limitations also apply to antennas employing ferrite scanning. The inductance in the biasing magnetic fields limits the scan rates and rate-of-change of scan rates attainable. At high scan rates the power requirements become large and the phase-shifters heavy. Another important limitation of ferrite phase-shifters is that hysteresis effects in the magnetic material cause difficulties in accurate resetting of the desired phase shift.

The traveling-wave tube has long been known as an excellent phase shifter, and tubes have been constructed for use at frequencies ranging from as low as 100 mc to as high as 100,000 mc. The phase-shift introduced by a traveling-wave tube is a sensitive function of its helix voltage and can be varied over several wavelengths with negligible control power. The traveling-wave tube is a very broadband and fast acting device which shows no appreciable hysteresis or temperature sensitivity and possesses a linear control function.[24] It should be recognized that the TWT has one important disadvantage when used as a phase shifter, the fact that it is a non-reciprocal device. This disadvantage is somewhat offset by the fact that a gain in power is realized by the phase shifter while all other devices accomplish phase shift with some associated insertion loss.

Another type of electronic phase shifter involves the use of gas devices. It is well-known that a variation in the degree of ionization in a plasma medium will produce an effective variation in dielectric constant. An effective plasma region is inserted within the transmission line to produce a phase shifting device (operating principle of Fig. 14a). A variation in the voltage controlling the degree of ionization provides variation in phase velocity along the line. Some studies of this problem have indicated that the gas tube phase shifter has severe limitations. From a power-handling standpoint, it is difficult to obtain a wide dynamic range since sufficiently high powers can cause variation in ionization in addition to that produced by the control voltage. The gas device has a higher noise figure than other phase shifting devices, and a shorter operating life due to cathode operation at relatively high pressures.[25]

The controlled elements discussed so far have been phase shifters operating in the configuration of Fig. 14a. The use of diodes as a controlled element requires the circuit arrangement of Fig. 14b. The β controlled sections consist of lengths of transmission line (L and $L + \frac{\lambda}{2}$). If the transmission line is terminated with a perfect varactor diode biased in the reverse direction total reflection will occur. The angle of the reflection coefficient is a function of the terminating capacitance which in turn is a function of the reverse bias voltage. A change in the reverse bias voltage of the diode thus produces the desired phase shifting operation. The finite resistance of the reverse-biased varactor diode will result in incomplete reflection and the phase shifter will have an insertion loss. A second diode device results in a time delay. The β controlled sections consist of short-circuited lengths of transmission line of length L and L + $\frac{\lambda}{2}$. A diode shunting the line is placed a distance ΔL (Fig. 15) from the shorted end of the line. In the forward-biased state the diode presents effectively a short circuit and the length of line ΔL is removed from the circuit. For a line propagating the TEM mode this corresponds to the removal of a fixed time delay $\frac{2\Delta L}{V_p}$ which is independent of frequency. In the reverse - biased state the diode is an open circuit, thus adding the incremental line length ΔL. It is obvious that this is a binary device and could be used only as a building block in the construction of a time delay device possessing the desired range of time delay steps. The varactor diode has a limited use due to its low power handling ability. The time delay device using existing PIN diodes can at the present state of the art handle peak-power in excess of 2 kw and average power greater than 60 watts.

System studies indicate that signal bandwidths as great as 10 percent at L-band might be required of high-power array radars. This bandwidth is too large for a simple phased array, one where all steering delays are modulo 2π radians, if the beam width is to be much smaller than 5°. The classical solution to this problem is to replace the phase shifters with true time delay shifters. Time delay shifters have at least two significant disadvantages. First, the precision required corresponds

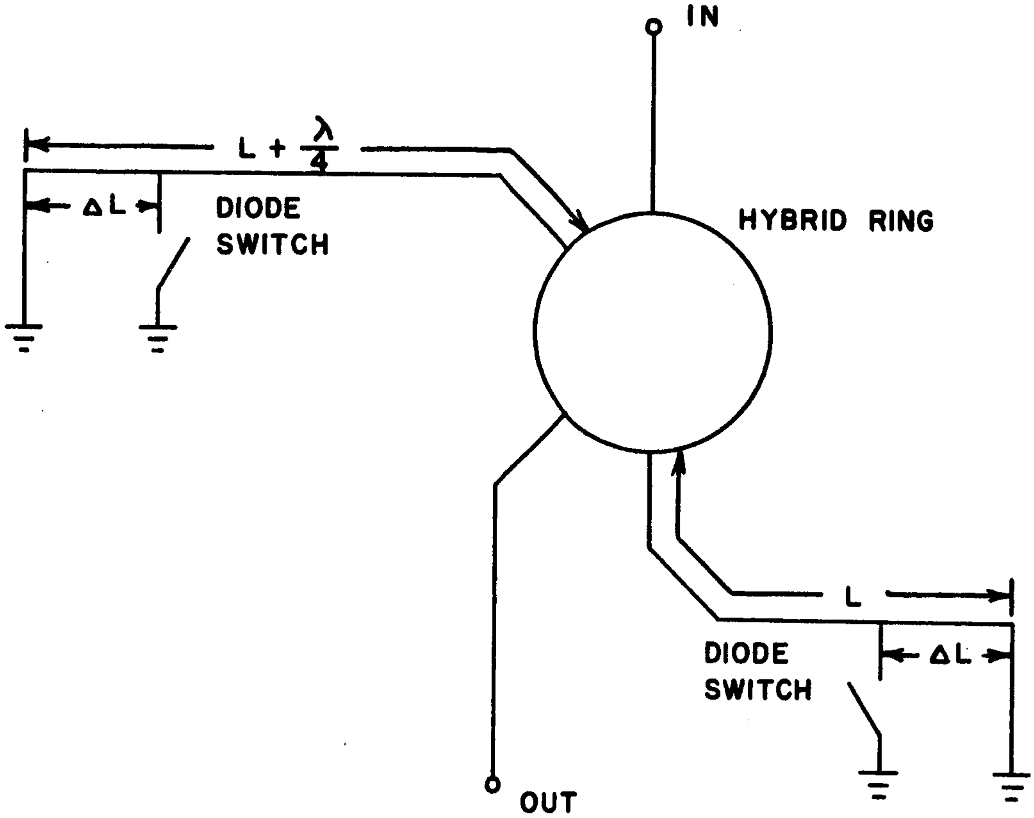


Fig. 15. Time Delay Device

to the number of beam positions to be used, and second, the introduction and removal of many wavelengths of delay cause undesirably large changes in the loss through the shifter. The hybrid array suggests itself as a reasonable compromise solution. It can be developed by dividing a large parallel-fed phased array into subarrays small enough so that buildup time (time interval required for the leading edge of a wavefront to illuminate all array elements) is not a problem. The individual subarrays may then be driven by true time delay shifters. This arrangement (depicted for a linear array in Fig. 16) would reduce the number of complicated time delay shifters required and, hence, would reduce the penalty in efficiency and complexity paid for added bandwidth.[26]

3.24 Beam Forming Matrix

The beam-forming matrix feed structure can be constructed utilizing corporate power distribution or traveling-wave power distribution. The corporate power distribution matrix will be discussed first.

Recent tests and experiments at Lincoln Laboratory on a 900 mcps RF beam forming matrix have demonstrated the effectiveness of this technique for use in phased array receiving systems. The matrix forms "n" overlapping fixed beams in space from an "n" element linear array antenna in an ideally lossless and completely passive manner using an intricate inter-connection of directional couplers and fixed phase shifters. The major advantages of this beam forming technique are: (1) it forms simultaneous multiple beams each of which have the full gain of the array aperture, and (2) it is a passive device which can be made very reliable and rugged.[27]

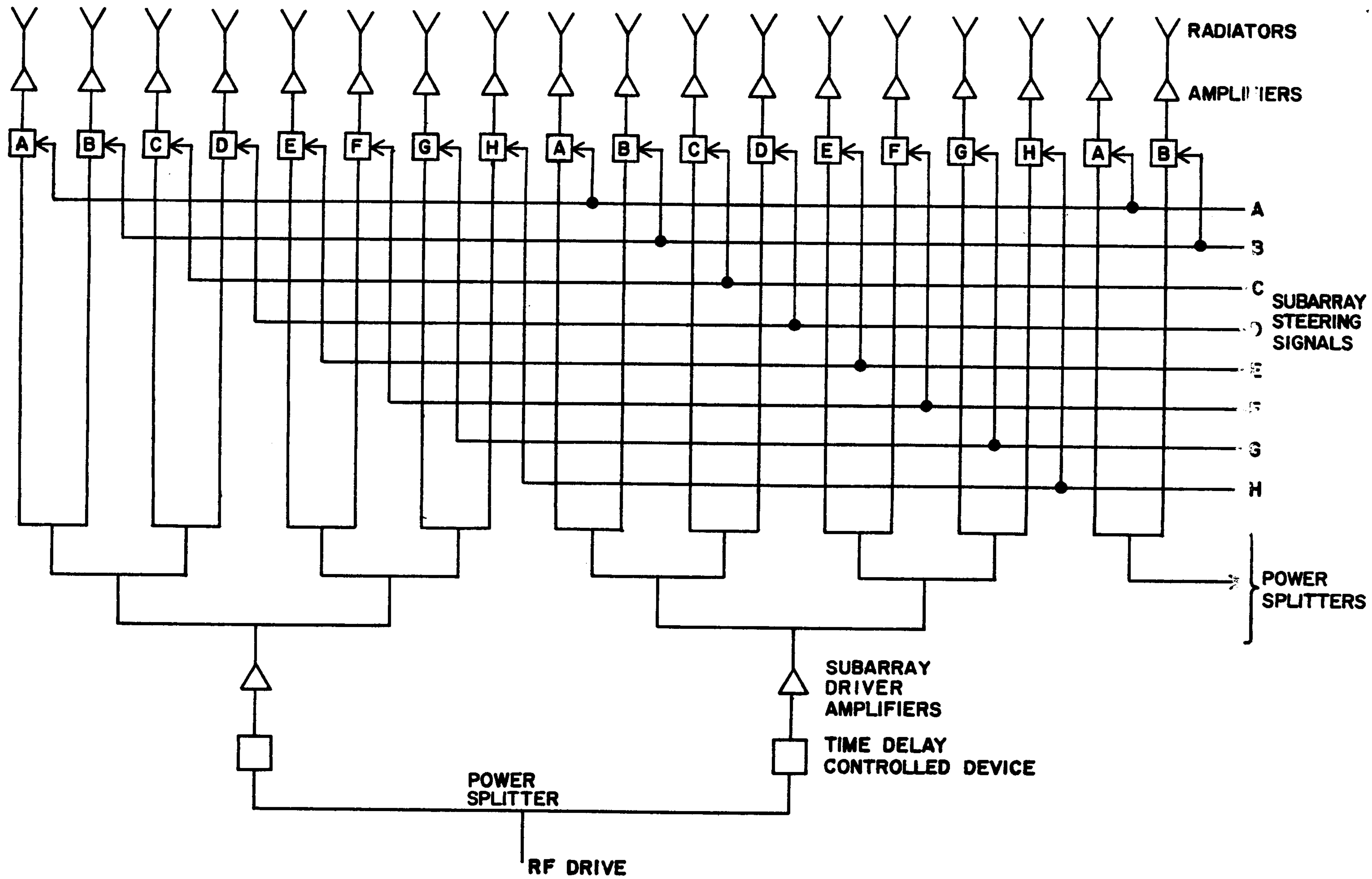


Figure 16. Section of linear hybrid transmitting array.

The basic components of the beam forming matrix are 3 db directional couplers or hybrid rings and fixed phase shifters. Before explaining the operation of the matrix it is necessary to adopt some conventions concerning the phase shift through hybrids and directional couplers. The conventions used are shown in Fig. 17. When the input voltages have the amplitudes and relative phase angles shown in Fig. 17 all the input signal power will come out the indicated terminal. Now it is possible to form the simplest multi-beam array by using two antenna elements and one hybrid ring or one 3 db directional coupler. Figure 18 shows a 2-beam, 2-element array using a 3 db directional coupler. A particular incident wavefront excites antenna element currents that are 90° out of phase, and therefore all the received signal energy comes out one terminal on the directional coupler. Thus a "beam right" and a "beam left" are formed.[27]

A four-beam matrix can be built by interlacing two two-beam matrices and then providing a second level of directional couplers or hybrid rings to combine the output beams. It is necessary to insert fixed phase shifters between the upper and lower level of couplers to form the output beam. Figure 19 shows a four-element, four-beam array using directional couplers. The amplitudes and phases of an incident "beam 1 left" signal are shown at various points in the matrix. Thus, it can be seen that the beam forming matrix behaves like a multiple parallel feed structure which routes a signal originating at a particular point in space to a particular output port of the matrix. An eight-element beam forming matrix can be thought of as two interlaced four-element matrices with an extra level of phase shifters and directional couplers to form the beam.[27]

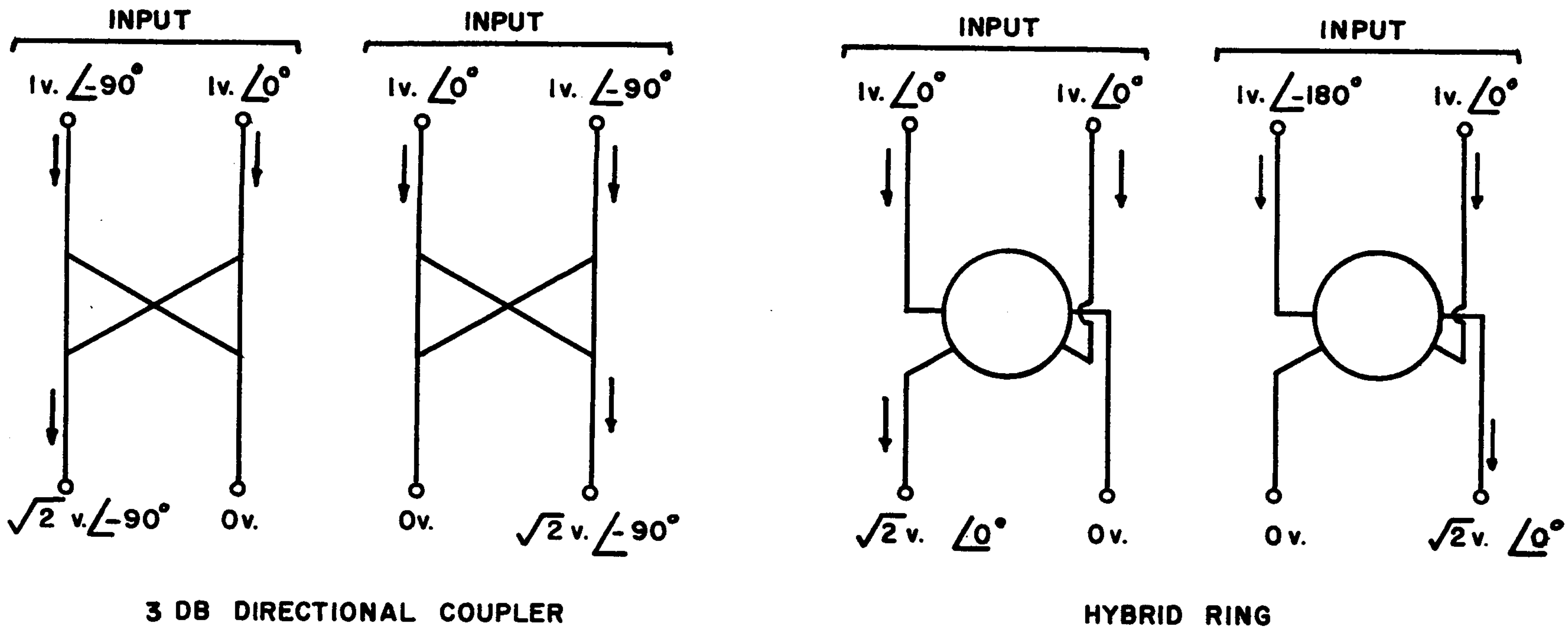


Fig. 17. Phase shift conventions for directional couplers and hybrid rings.

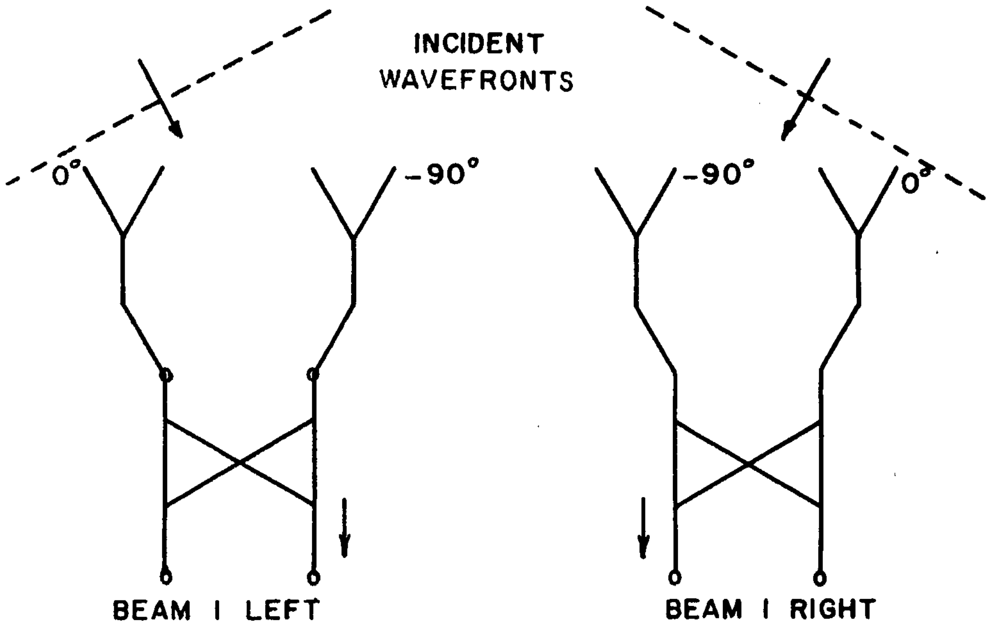


Fig. 18. Simplest beam forming matrix.

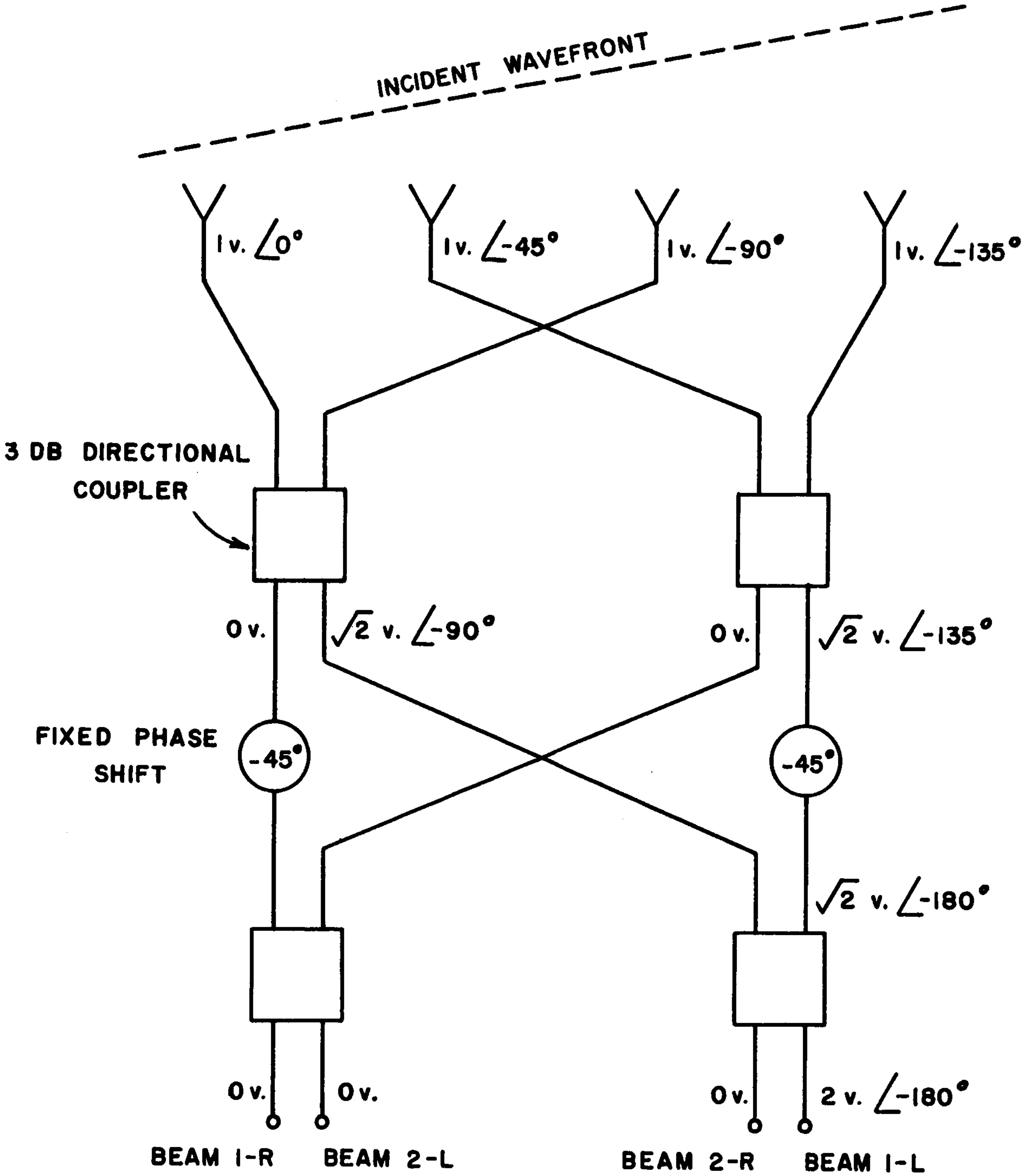


Fig. 19. Amplitudes and phases of a "beam 1-left" signal.

The design procedure for an N-element array specifying the values of all the fixed phase shifters and beam inputs has been published by H. J. Moody.[28]

The beam forming technique can be used in planar arrays by first combining the columns of antenna elements in matrices and then combining the outputs of the column matrices in a group of row matrices. Some of the fundamental characteristics of the beam forming matrix are discussed below.

The number of beams formed is equal to the number of antenna elements used. The number of antenna elements in the array must be equal to a power of 2. The operating frequency is limited only by the practicality of building and interconnecting fixed phase shifters and directional couplers. The matrix provides a uniform illumination of the aperture. However, simple beam combining techniques can yield $(\text{cosine})^n$ illuminations.[27]

Considered from an antenna standpoint, the major advantage of this technique is the realization of simultaneous multiple beams, all of which have the full gain of the aperture. Rather than having to steer a single beam using, for example, RF phase shifters, one has only to observe the outputs of the matrix in a selective or simultaneous manner.

Since the matrix is theoretically lossless (and in practice has a low insertion loss) it can be located directly behind the antenna elements with a resultant saving in phase and gain-stable high frequency circuits. The microwave elements used in the matrix are passive and non-variable, thus the matrix can be made rugged and reliable using strip transmission line techniques. The matrix itself can be made broadband, but the frequency limitations of phased arrays (as opposed to a time-delayed array) are still present.

A possible drawback of this beam forming technique from an antenna standpoint is that the simultaneous beams are fixed in space. In radar applications however, Ross and Schwartzman[29] have described how continuous null tracking of a target may be achieved with a fixed pattern multiple-beam forming matrix with a resulting improvement in tracking accuracy when compared to beam interpolation techniques.

For large element arrays the complexity of the matrix arrangement (transmission line crossovers) complicates the fabrication, and will also make it more difficult to achieve very low matrix insertion loss for use in low noise antenna systems. The system is limited in power handling capability by the high power characteristics of the transmission lines and connectors used. Also, since the matrix behaves like a power divider, the bottom directional couplers and phase shifters will have to handle much higher powers than the upper ones.

A beam-forming matrix can be constructed utilizing traveling-wave power distribution. The technique is shown in Fig. 20. The angle of intersection of the feed line with the radiating line determines the relative phase shift between adjacent radiators and hence the beam direction. The amount of coupling from the feed line to the radiating line determines the type of aperture illumination (constant, tapered). The matrix can be constructed in a compact form with rectangular wave-guide.

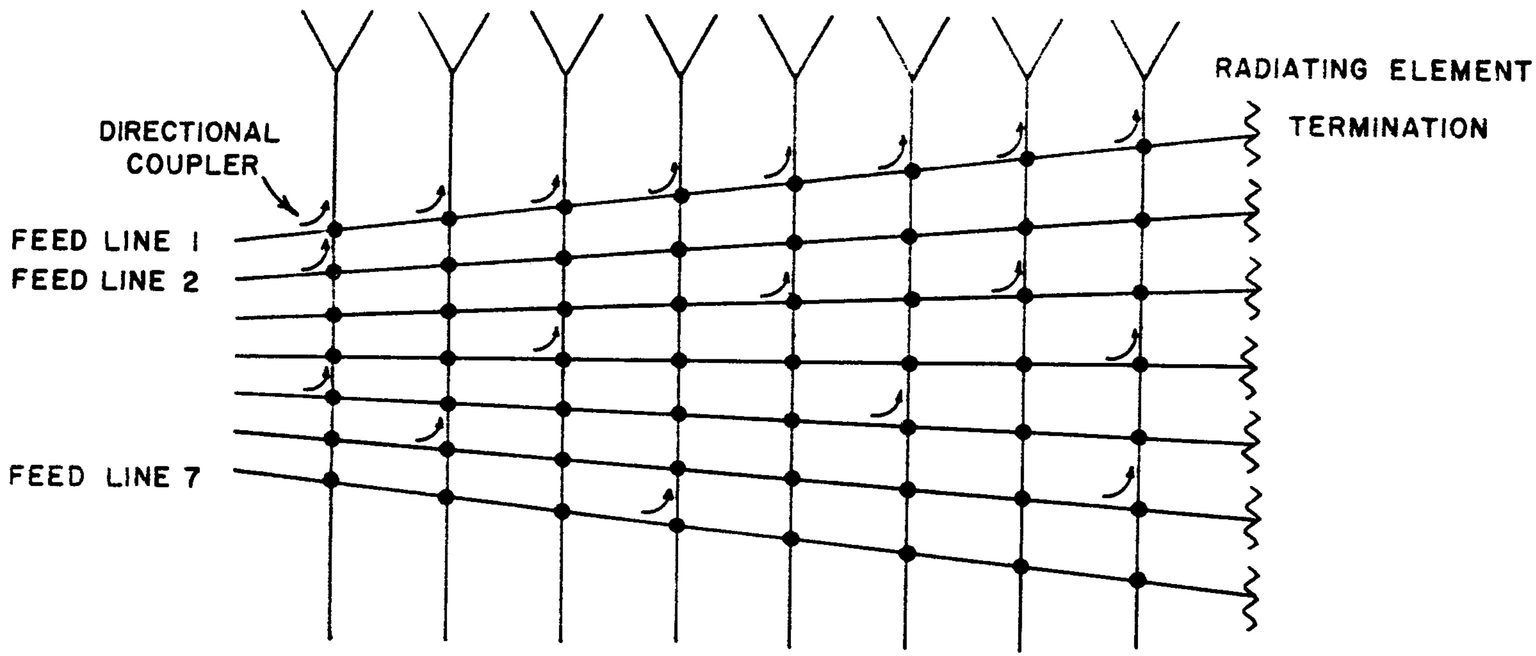


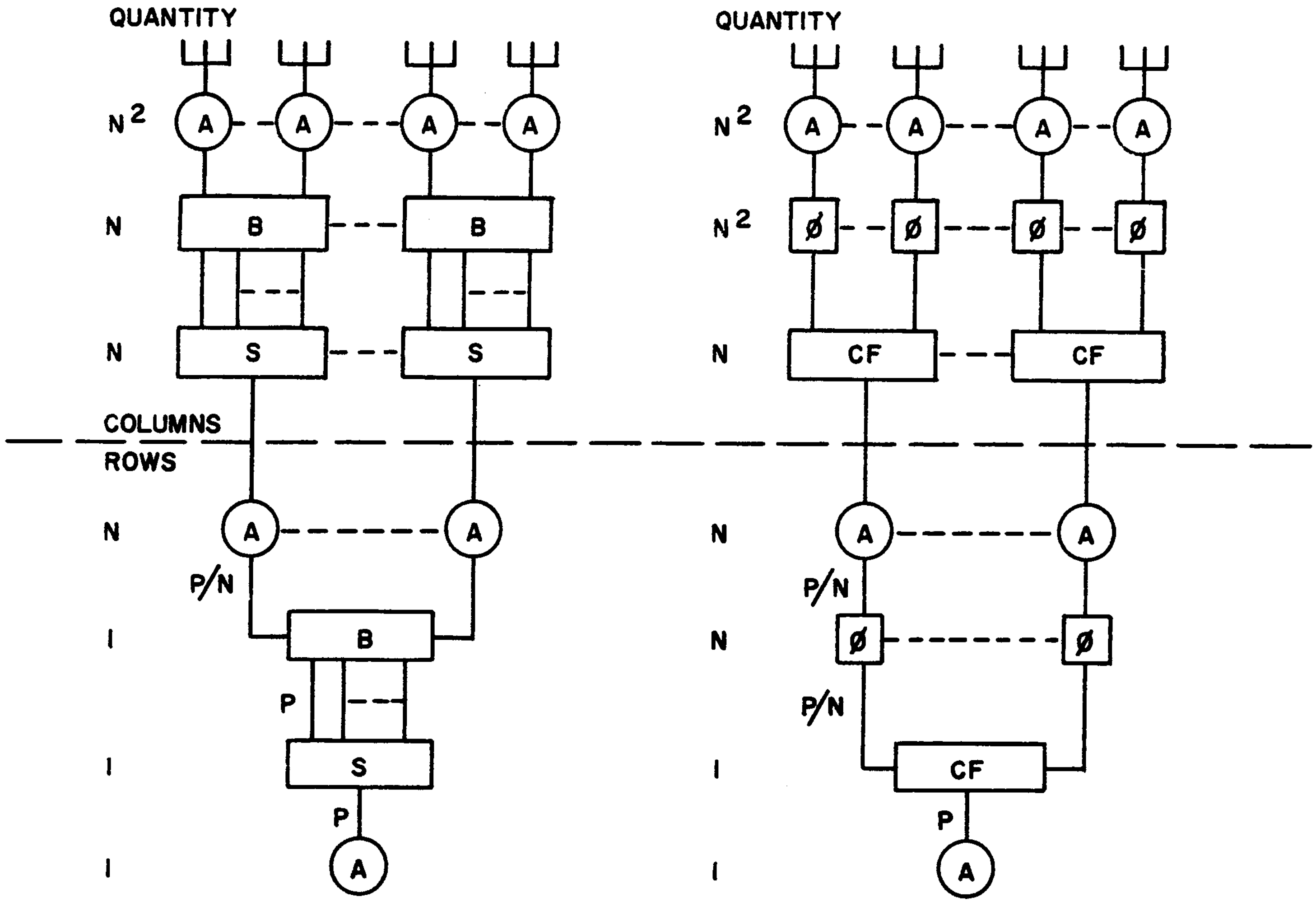
Fig. 20. A traveling wave beam-forming matrix schematic.

3.25 Applications

At lower frequencies (where strip transmission line is effective) the parallel-fed multibeam-forming matrix promises to be a better solution for the receiving feed structure for reasons of reliability and insertion loss. However, high power phase shifters appear to be a better solution for the transmitter for reasons discussed below.

Two transmitter approaches are depicted in block diagram form in Fig. 21. Obviously, in both approaches, it is desirable to keep the number of N^2 system elements to a minimum and the element itself as simple and reliable as possible. Consider, for example, the consequences of a simple single stage terminal amplifier. This means the input amplifier power should be high. In fact, the row amplifier (N in number) should be at least as large as the terminal amplifier. The consequence of these arguments leads one to search for methods of high-power phasing. Further examination of Fig. 21 shows that the high-power phasing requirement is more severe in the multibeam-forming appraoch than in the parallel-fed approach. The multibeam-forming approach requires a selector switch and a multibeam-forming matrix which has a power handling capability P. The parallel-fed approach requires a controlled element with power handling capability of only P/N. Thus, the parallel-fed approach is considered the desirable one for transmitters.[23]

W. P. Delaney[27] describes a 16-element beam-forming matrix which has been tested extensively in the laboratory and in a linear array antenna system. The matrix was constructed with strip line components to operate at 900 mc. Antenna patterns were recorded for uniform illumination and for $(\text{cosine})^n$ illumination.



A AMPLIFIER
B N-PORT MULTIBEAM FORMING MATRIX
CF CORPORATE FEED
P POWER
ø CONTROLLED ELEMENT
S N-POSITION SELECTOR SWITCH

Fig. 21. Two Transmitter Approaches.

A retrodirective satellite antenna for a broad bandwidth satellite-to-ground data transmission link is proposed in a paper by C. A. Belfi, et al.[33] The satellite antenna described for this system is an active retrodirective antenna which utilizes the beam-forming characteristics of a parallel-fed matrix.

The W. L. Maxson Corp.[30,31,32] constructed a traveling-wave beam-forming matrix to operate at 9 KMC. The test array consists of five feed lines (each corresponding to one beam) and 120 radiating elements. The design of the array and the results of various tests performed on the array are discussed.

The technique of phase scanning with traveling-wave tubes as the controlled element has been studied in a report by G. I. Cohn.[39] He gives the results of measurements on a series-fed nine-element receiving array. In this model antenna signals received by each of the lineal array elements are impressed and stored on the electron beam as it passes each of the antenna-to-electron-beam couplers. Thus the electron beam acts as the traveling wave medium in which the signals from the successive antenna elements are superimposed. At the output end of the electron beam a signal which is the superposition of all the impressed signals is removed.

A thirty-two element, center-fed, traveling-wave-feed, linear array was constructed at Bell Telephone Laboratories.[21] The controlled elements are X-band ferrite phase shifters. The results of several tests on the array and array patterns are included in the referenced report.

3.3 Time Modulated Array

3.31 Principle of Operation

In a recent paper[34], the application of time domain techniques to antenna systems was described, and in a preliminary way shown to provide a means for quasi-electronic scanning. The basic philosophy of time domain antennas is centered around the recognition that if some parameter of an antenna (length, shape, aperture excitation, etc.) is modulated in a periodic manner, the time-varying radiation pattern can be written in one form as

$$G(\theta,t) = A\left[b_0(\theta) + b_1(\theta)\cos\omega_0 t + b_2(\theta)\cos 2\omega_0 t + \ldots\right] e^{j\omega t} \;;$$

where the $b_n(\theta)$ are in general different spatially dependent patterns, ω_0 is the modulation frequency and it is assumed that $\omega_0 \ll \omega$. Because of the independent nature of the ω_0 harmonics, each term in the series can be independently detected to provide a series of signals, each having different spatial pattern characteristics. For the special case in which the spatial patterns are pencil beams pointing in different directions, the strength of a given harmonic $n\omega_0$ will give a direct indication of the presence and strength of a target in the corresponding direction.[35]

The basic features of utilizing the time domain philosophy to achieve electronic scanning can be seen by consideration of a continuously excited linear array. Suppose that $2N + 1$ pencil beams are desired from an array of length $2l_0$, with the spacing between beams of the order of θ_0. In addition, each of these patterns is associated (i.e. "tagged") with a different frequency component. In mathematical language, these conditions are expressed by

$$g(\theta,t) = \sum_{n=-N}^{N} \frac{\sin\left[kl_0(v - nv_0)\right]}{v - nv_0} e^{j(\omega + n\omega_0)t} , \qquad (1)$$

where $g(\theta,t)$ is the desired time varying pattern complex, ω_0 is the fundamental modulation frequency and v and v_0 are, respectively, sin θ and sin θ_0. In a practical system, the value of v_0 and the number of beams, 2N + 1, would be chosen to give the desired angular coverage and detection accuracy. Examination of (1) discloses an excellent picture of the scanning mechanism; a target in the vicinity of the angular direction $n\theta_0$ will be directly associated with the frequency $n\omega_0$. From another viewpoint, (1) represents a frequency spectrum in which the upper and lower sideband magnitudes indicate the strength of targets in the associated directions.[35]

The aperture distribution to give the pattern characteristics of (1) may be found by the application of Fourier integral theory. This distribution is

$$f(x,t) = \sum_{n=-N}^{N} e^{-j(kv_0nx - n\omega_0t)} . \qquad (2)$$

This expression can be considered as a series of traveling amplitude waves moving from left to right along the array. Because of the equality of these wave amplitudes, the complete sum will resemble an exciting pulse traveling across the array. Thus it is seen that in order to realize the pattern complex of (1), the linear array must be excited progressively, a small portion at a time. Because of the choice of a finite number of terms of (1), the pulse shape as determined by (2) is not of simple form. However, it can be shown that rectangular pulse excitation, accomplished by on-off switching of the elements of a linear array, will produce the desired scanning.

3.32 Applications

The basic theory of operation of a time modulated receiving array is outlined and the switching requirements are discussed in a report by W. H. Kummer, *et al*.[36] Patterns of a five-element linear array are presented and the auxiliary equipment necessary for implementing the technique is considered.

Work at Hughes Aircraft Company[37,38] has demonstrated the technique of time modulated arrays with a 20-element slot array which incorporates sequential on-off switching of the array elements. Patterns showing the scanned beams both individually and superimposed are included in the reports. The beam pointing directions correspond to the theoretical predictions.

CONCLUSIONS

Electronic steering of antennas offers significant advantages over mechanical steering. It is inertialess and therefore relatively very fast. The electronically scanned array gives a fixed surface which is of importance on an airframe. Transmission and reception by arrays are reliable in that failure of one array element does not degrade system performance greatly; in fact the passive Van Atta retrodirective array offers the ultimate in reliability. Electronic scanning also allows a variable beamwidth, and gain, not possible with mechanical scanning. Finally, electronically steered arrays offer the possibility, for ground stations, of a greater gain than is possible with large single-aperture antennas which are limited by manufacturing tolerances and phase perturbations in the propagating medium. This last advantage has not yet been realized in practice.

A disadvantage of scanning by arrays is increased system complexity, as indicated in this report by the drawings which show the phase shifters, couplers, amplifiers, etc. which may be associated with each array element. It is quite fortunate, however, that system reliability is not necessarily decreased and, in fact, may be increased since, as was pointed out above, failure of one array element does not cause overall performance to deteriorate greatly.

Other disadvantages associated with this increased complexity are increased costs and decreased bandwidths.

It seems probable that many applications for these electronically scanned arrays will be found. This report has discussed the advantages and disadvantages of the various scanning methods which have been constructed or proposed thus far, and in many cases reference to these system characteristics will suggest the most suitable method for a particular application.

The field of electronically scanned arrays is relatively new. As of March, 1964, when a special issue of the IEEE Transactions on Antennas and Propagation concerned with this area was published, some of the methods discussed in the literature were speculative only and had not been developed experimentally. Since that time additional development has of course taken place, but no significant new scanning technique has, to the knowledge of the authors, been proposed. Many of the papers in this area have appeared in the open literature, and this fact is indicated by the number of open references cited. Many of the references are Defense Documentation Center (DDC, ASTIA) publications, and these were found to be highly useful. Little was found of a useful nature in the classified literature that does not also appear in the unclassified, and only one such reference was cited.

This study has indicated that while much work has been done in electronic array scanning in the relatively short time since the concepts were first introduced, much remains to be done. One problem of evident importance is that of the production of harmonics by the controlled elements of the array, such as diodes. This can result in radiation of undesired signals in the pass band of some nearby receiver. Another area in which studies are needed is that of mutual impedance effects between the elements of an array. One result of such effects is that the input impedance of each element varies with scan angle, causing mismatch losses with consequent lower radiated power.

Other important problems needing further study are: acquisition at low signal-to-noise ratio, design of wide bandwidth systems, scanning over large angles, and system operation with more than one signal.

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