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Conjugate-Pair Feed Systems

M. L. Reuss, Jr.

Microwave Antennas and Components Branch
Electronics Division

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Abstract: Two microwave feed circuits have been developed for use in electronically scanned antenna arrays. Both of these circuits offer advantages over the conventional circuits employing nonreciprocal phase shifters of the digital type. The first circuit permits reduction in the number of phase shifters by requiring one phase shifter for each pair of radiating elements rather than the usual phase shifter per radiating element, while the second circuit permits simultaneous reception and transmission of signals with independent control of the transmit and receive beam directions.

An X-band model was constructed, and radiation patterns were obtained from a seven-element array fed by these circuits. The results demonstrate the feasibility of both circuits.

INTRODUCTION

The current trend in the field of microwave antennas is toward the increasing use of electronically scanned antenna arrays. Two feed circuits offering advantages over the conventional circuits have been developed for use in these antenna arrays. Both circuits employ nonreciprocal phase shifters of the digital type.

The first circuit, a nonreciprocal system requiring switching between the transmit and receive pulses, permits reduction of the total number of phase shifters by requiring one phase shifter for each pair of radiating elements rather than the usual phase shifter per radiating element.

The second circuit, a reciprocal system, permits simultaneous reception and transmission of signals, with independent control of the transmit and receive beam directions.

DESCRIPTION

In scanning a linear array, the excitation phase of the individual elements is such as to always represent a linear phase progression from element to element, the difference between any two adjacent elements determining the angle of scan of the beam. It is convenient to consider the phase of the center element of the array to be fixed and the radiated phase front to be a straight line that rocks to right or left about the center element.

NRL Problem R08-36; Naval Electronic Systems Command S-1617. This report completes one phase of the problem; work is continuing on other phases. Manuscript submitted April 21, 1966.

Consider now any two elements which are equidistant from the center of the array—as, for instance, the elements A and B of Fig. 1. For any scan position of the beam, the phases at A and B will be conjugate. Thus, if A in Fig. 1 represents a phase lag of ϕ degrees, B will at the same time represent a phase advance of ϕ degrees, and vice versa. (Here phase advance and lag are relative to the center element, whose phase is assumed to be constant at 0 degrees.)

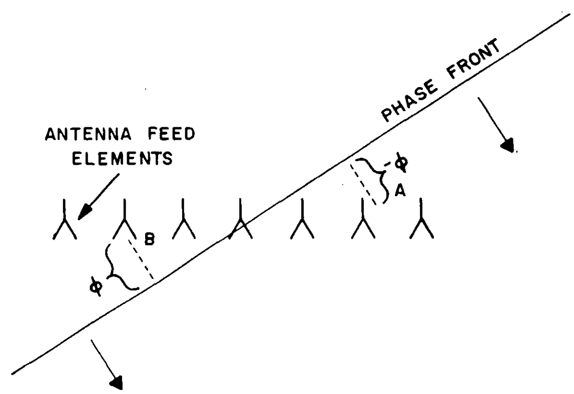

Fig. 1 — Position of phase front relative to center element

Scanning or changing the direction of the main beam requires establishing the proper conjugate phase relation between element pairs such as A and B. This conjugate phase relationship can be accomplished by means of the microwave circuits shown in Figs. 3 and 4, which will be discussed later; however, both of these circuits require a conjugate phase shifter.

CONJUGATE PHASE SHIFTER

A conjugate phase shifter which can produce a phase advance for a signal traveling in one direction while simultaneously producing a phase delay for a signal traveling in the opposite direction is readily obtained by applying one restriction to the nonreciprocal digital latching ferrite phase shifter.* In practice this digital phase shifter consists of several sections, or "bits," that can be individually activated. Each bit yields an incremental phase shift $\Delta\phi_i$ that is the phase difference between the electrical lengths for each direction of propagation:

$$\Delta\phi_i = |\beta_+ \ell - \beta_- \ell|$$

where ℓ is the length of the ferrite-loaded line, β_+ is the propagation constant for the positive direction (or current state), and β_- is the propagation constant for the negative direction.

Thus the phase shift through a bit will be $\Delta\phi_i$ or zero, depending on the manner in which the bit is energized. If the restriction is placed upon this digital phase shifter that:

$$\Sigma\, \Delta\phi_i = 360,$$

it can be seen that a conjugate phase shifter results. Let $\Delta\phi_i^+$ and $\Delta\phi_i^-$ represent phase shifts inserted for waves traveling in the positive and negative directions respectively; then consideration of the definition of $\Delta\phi_i$ requires $\Delta\phi_i^+$ to be zero when $\Delta\phi_i^-$ is non-zero, and the converse. Then:

$$\Sigma\, \Delta\phi_i^+ + \Sigma\, \Delta\phi_i^- = 360°,$$

or

$$\Sigma\, \Delta\phi_i^+ = 360° - \Sigma\, \Delta\phi_i^- = -\Sigma\, \Delta\phi_i^+$$

which yields the required conjugate relationship.

Consider a digital phase shifter consisting of five bits having values of 15, 30, 45, 90, and 180 degrees. For purposes of illustration let each bit consist of a section of shorted transmission line attached to a three-port switchable circulator, as shown in Fig. 2. The arrows denote the direction of circulation of each circulator. A signal traveling from L to M passes through the shorted transmission lines attached to circulators I and III, resulting in a phase shift of 60 degrees. A second signal traveling in the reverse direction, from M to L, would pass through the shorted transmission lines of the remaining circulators, II, IV, and V, producing a phase shift of 330 degrees or −60 degrees. By choosing the direction of circulation for each of these circulators, it is possible to choose any multiple of 15 degrees from 0 to 360 degrees and automatically obtain its conjugate. Naturally this type of phase shifter is not limited to 15-degree increments, which were used for convenience of illustration only.

*During the remainder of this report, this type of phase shifter will be referred to simply as a digital phase shifter.

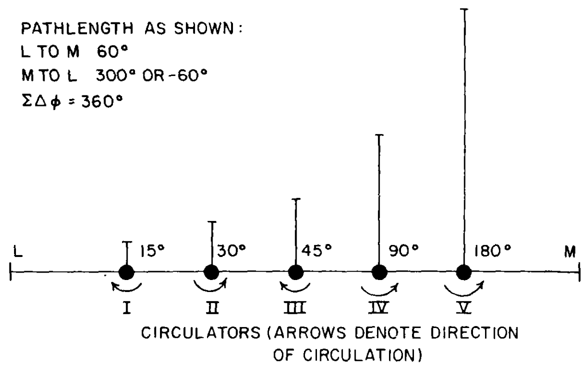

Fig. 2 – Conjugate phase shifter

NONRECIPROCAL CONJUGATE-PAIR FEED SYSTEM*

As previously mentioned, the conjugate phasing of element pairs such as A and B can be achieved by the microwave circuit shown in Fig. 3. The action of this arrangement, shown in the transmit state, is as follows. The signal entering at F is divided equally to right and left at tee G. Switching circulators at L and M direct these two signals, now traveling in opposite directions along line L-M, into the conjugate phase shifter lying along this line. As all the corresponding transmission-line lengths (*e.g.*, G to L, = G to M, L to $A = M$ to B, *etc.*) are equal, the relative phases of the signals leaving the phase shifter are conjugate. These signals are re-directed by circulators L and M to elements A and B, where they are radiated with the required conjugate phases.

*This feed system was suggested by Dr. Arthur E. Marston of the Naval Research Laboratory.

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which yields the required conjugate relationship.

Consider a digital phase shifter consisting of five bits having values of 15, 30, 45, 90, and 180 degrees. For purposes of illustration let each bit consist of a section of shorted transmission line attached to a three-port switchable circulator, as shown in Fig. 2. The arrows denote the direction of circulation of each circulator. A signal traveling from L to M passes through the shorted transmission lines attached to circulators I and III, resulting in a phase shift of 60 degrees. A second signal traveling in the reverse direction, from M to L, would pass through the shorted transmission lines of the remaining circulators, II, IV, and V, producing a phase shift of 330 degrees or −60 degrees. By choosing the direction of circulation for each of these circulators, it is possible to choose any multiple of 15 degrees from 0 to 360 degrees and automatically obtain its conjugate. Naturally this type of phase shifter is not limited to 15-degree increments, which were used for convenience of illustration only.

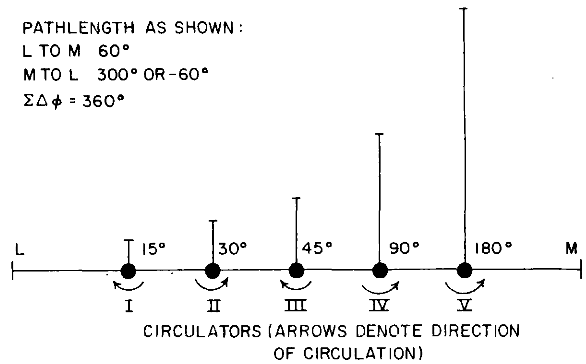

Fig. 2 — Conjugate phase shifter

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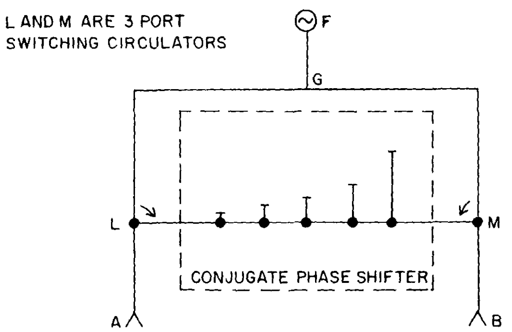


Fig. 3 – The nonreciprocal conjugate-pair feed system

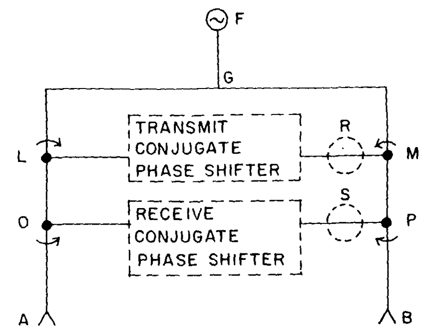


Fig. 4 – The reciprocal conjugate-pair feed system

The previous paragraph is a description of what happens when a signal is transmitted in a given direction. When a signal is received from this direction, it is necessary to reverse the sense of the circulators and phase shifters.

If over two bits are incorporated in the phase shifter, there is a decrease in the number of active elements required in the above conjugate pair arrangement, as compared to the usual arrangement that employs a separate phase shifter for each radiating element.

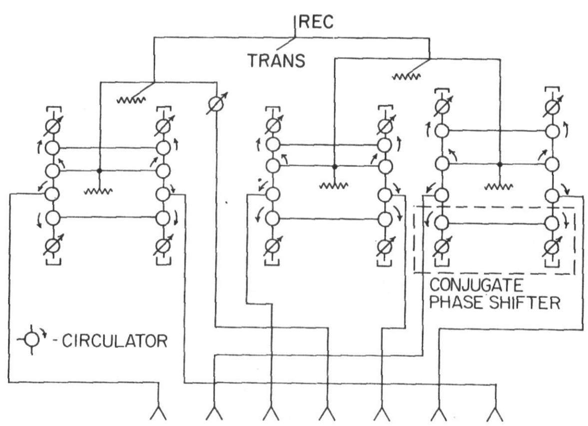
RECIPROCAL CONJUGATE-PAIR FEED SYSTEM

The nonreciprocal conjugate-pair feed system can be converted into a reciprocal system by the addition of two circulators and a second conjugate phase shifter, as shown in Fig. 4. On transmission, the action of this system is identical to that of the previously discussed system until circulators *O* and *P* are encountered. These fixed circulators (circulators *L*, *M*, *O*, and *P* are not of the switching type) direct the signals around the receive phase shifter and to the radiating elements *A* and *B*, where they are radiated with conjugate phases. Consider the case where the input signals return from a given direction (*i.e.*, the signals have, in regard to this antenna, conjugate phases). The signals entering via elements *A* and *B* are directed by circulators *O* and *P* into the receive conjugate phase shifter, where their phases are adjusted to the in-phase condition for this particular beam direction. After leaving the phase shifter, the two signals are again directed by circulators *O* and *P* to circulators *L* and *M*, guided around the transmit phase shifter by these circulators (*L* and *M*), and combined at *F* by tee *G*. Thus it can be seen that the only active elements in this array are the two phase shifters.

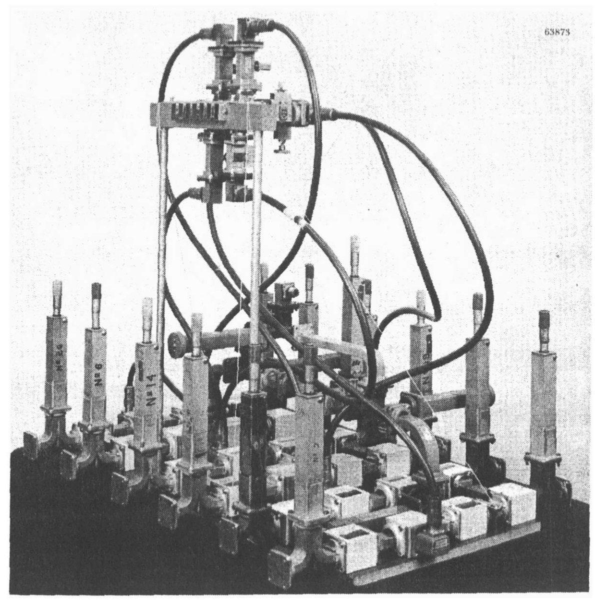
If the receive and transmit beam directions are the same, the computer programming is simplified, since the transmit and receive phase shifters are energized by the same command. However, this system introduces flexibility, in that independent control is possible for the transmit and receive beam directions via independent control of the transmit and receive phase shifters. In addition to this independence of transmit and receive beam directions, independent amplitude distributions may be obtained by insertion of attenuators at positions *R* and *S* of Fig. 4.

EXPERIMENTAL ARRAY

A linear, seven-element, reciprocal conjugate-pair array was built and tested at 9.2 GHz. Both a schematic and photograph of this array can be seen in Fig. 5. An element spacing of approximately 0.6 λ was used, and a 17-bd Dolph-Tchebycheff amplitude distribution was obtained by the use of attenuators preceding the radiating elements. Each conjugate digital latching ferrite phase shifter was simulated by using two circulators with opposite senses of circulation, and one transmission line associated with each circulator was terminated in an adjustable short. When an incremental phase shift was inserted in one shorted line, this amount of phase shift was removed from the second line, thereby resulting in a pair of short positions corresponding to each bit state. The smallest bit size used was 30 degrees. Magic tees were used to form the corporate



(a)



(b)

Fig. 5 — The seven-element conjugate-pair feed-system array. (a) Schematic of the seven-element conjugate array. The dashed line encloses one conjugate phase shifter. (b) Laboratory model of array.

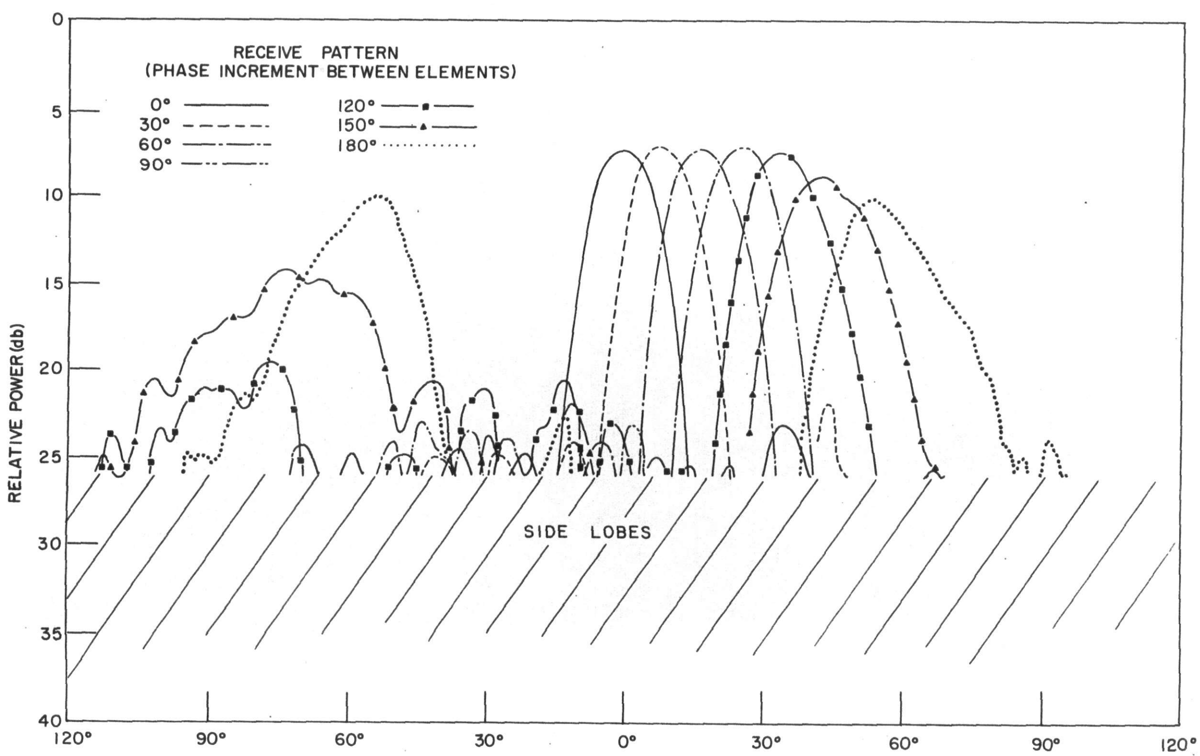


Fig. 6 — Typical radiation patterns of the conjugate-pair feed-system array

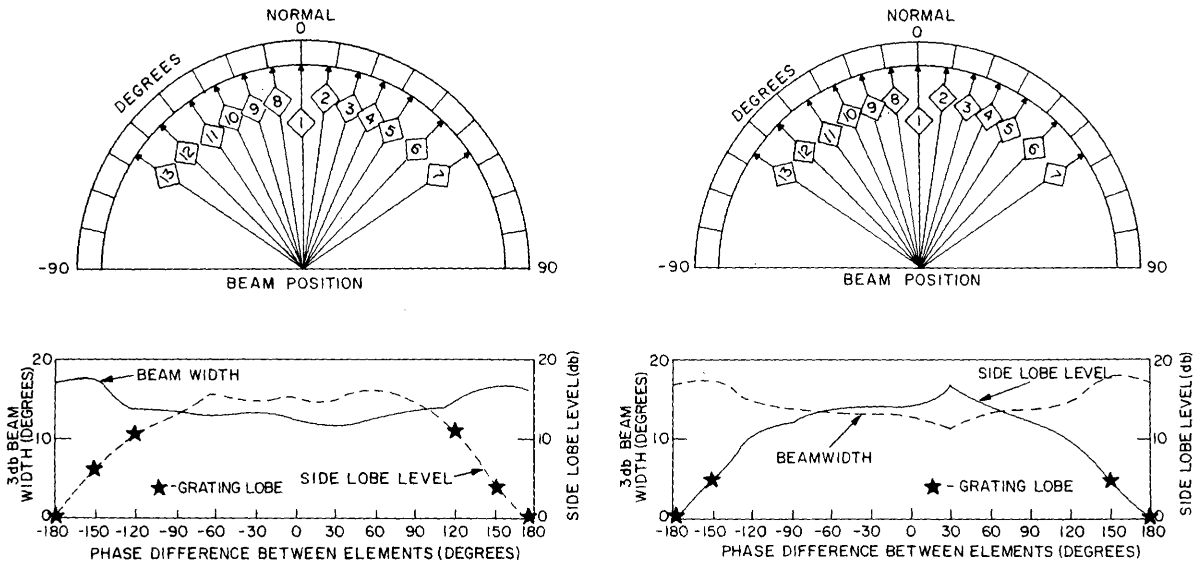


Fig. 7 – Summary of the radiating-pattern characteristics of the conjugate-pair feed-system array

structure feeding three conjugate-pair systems and the center element. For convenience, coaxial lines were used to connect the radiating elements to the feed system. The zero reading of the adjustable shorts was used to equalize the electrical line lengths.

Typical patterns obtained with the seven-element array are shown in Fig. 6. Deviation from the design sidelobes are attributed to variation in the amplitude distribution resulting primarily from mismatches within the corporate feed system. As would be expected, grating lobes due to the element spacing caused the radiation patterns to deteriorate rapidly when the beam was scanned about 45 degrees or more off axis.

Receive and transmit pattern data are presented in Fig. 7. Figure 7a presents the direction in space of the main beam as a function of phase difference between adjacent radiating elements, while in Fig. 7b both 3-db beamwidth and sidelobe level are presented as a function of the same variable. From Figs. 6 and 7 it can be seen that antenna systems utilizing the conjugate-pair circuits are feasible for linear arrays.

CONCLUSIONS

Two microwave circuits have been discovered that are suitable for use with state-of-the-art ferrite nonreciprocal digital phase shifters. The nonreciprocal system offers the advantage of fewer active elements and thus should reduce both cost and the computer problem. The reciprocal system, which also uses nonreciprocal phase shifters, combines the desirability of a reciprocal system with the switching-speed and holding-power requirements of the latching ferrite phase shifters. Independent control of the transmit and receive beam directions are attributes of this system, which might well be considered for satellite applications. An experimental model of the reciprocal system was built which demonstrates the feasibility of both the reciprocal and nonreciprocal systems.

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13. ABSTRACT

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