Duplexing Ferrite Reciprocal Phase Shifters

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***Abstract* — The basic structure of microwave ferrite reciprocal phase shifters of the Dual-Mode and Rotary-Field types can readily be adapted to incorporate the function of a circulator outside the phase shifting region. The circulator effect is realized in the form of orthogonal polarization of waves in the two directions of propagation in circular or square waveguide at the input of the device. A mode-separating waveguide junction is required to resolve these orthogonal modes into two single-mode waveguides.**

This paper presents specific implementations of duplexing ferrite reciprocal phase shifters, comments on the factors affecting the isolation of the equivalent-circuit circulator, and discusses possible advantages in antenna system applications.

***Index Terms* — Ferrites, phase shifters, circulators, duplexers, antenna arrays.**

I. Introduction

The basic interaction between a microwave frequency wave propagating in a ferrite medium with a steady magnetic bias field is nonreciprocal. That is, circularly polarized rf magnetic fields in the plane normal to the steady bias field interact differently with the ferrite medium for right-hand or left-hand rotation. The most efficient ferrite control devices are those which take maximum advantage of this phenomenon, and are consequently nonreciprocal. Dual-Mode [1], [2] and Rotary-Field [3], [4] phase shifters are no exception to this rule; they are in fact simply nonreciprocal devices whose configuration has been arranged to create reciprocal phase shift between the device terminals. The intrinsic nonreciprocal nature of these phase shifters allows a further adaptation to be made that provides duplexing.

For the usual Dual-Mode case, phase shifting takes place in a circular ferrite-filled waveguide with a longitudinal magnetic bias field whose magnitude and direction are settable. The circular waveguide can propagate both right-hand and left-hand circularly polarized waves in either longitudinal direction. Fixed nonreciprocal quarter-wave plates are located beyond both ends of the phase shifting region. These elements use a transverse fourpole magnetic bias field [5] to produce a frequency-dependent differential phase of approximately 90 degrees, and convert between linearly polarized waves at the device terminals and the circularly polarized waves needed in the phase shifting region. The nonreciprocal quarter-wave plates generate opposite senses of circular polarization in the phase shifting region for the two directions of propagation. Consequently the same sense of transverse-plane rotation of the rf magnetic field relative to the steady longitudinal magnetic bias field will exist, and the insertion phase changes will be independent of propagation direction. Fig. 1 shows typical block diagrams of a conventional Dual-Mode phase shifter.

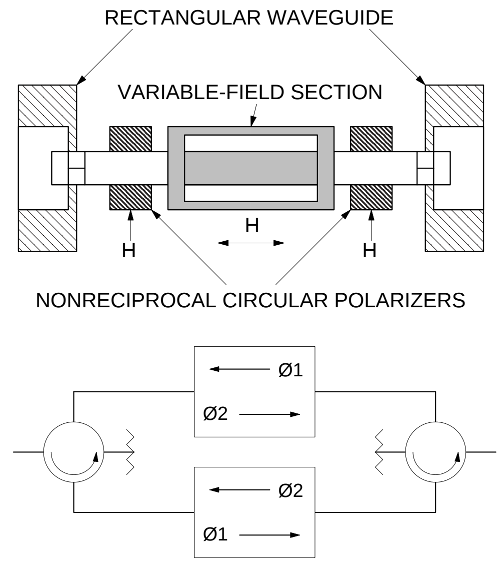

Fig. 1. Configuration sketch and functional block diagram for conventional Dual-Mode ferrite reciprocal phase shifter.

Operation of the Rotary-Field phase shifter is more subtle. In this case linearly polarized waves at the device terminals are converted to circular polarization by *reciprocal* quarter-wave plates. The phase shifting region is between the quarter-wave plates and consists of a rotatable ferrite half-wave plate, which is in turn realized by applying a rotatable transverse fourpole magnetic bias field to a circular waveguide completely filled with ferrite. The normal modes in this region are an orthogonal pair of waves polarized linearly in directions along the nulls of the bias field pattern. The bias field level and length of the region are selected such that the insertion phase difference between the two normal modes is 180 degrees, i. e. a half-wave plate is created. This ferrite half-wave plate is nonreciprocal, with the "long" and""short" normal mode directions reversed between the two directions of propagation. Phase changes result from rotation of the ferrite half-wave plate, and the direction and amount of change are the same for both directions of propagation. The nonreciprocal nature of the ferrite half-wave plate contributes a fixed difference of 180 degrees between the

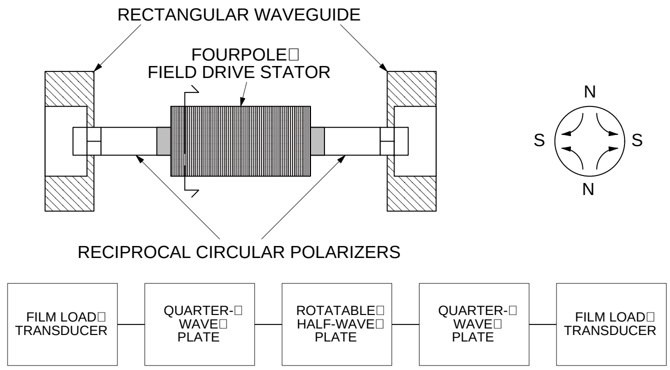

Fig. 2. Configuration sketch and block diagram of Rotary-Field ferrite reciprocal phase shifter.

insertion phases for the two directions of propagation. Fig. 2 shows descriptive diagrams of a typical conventional Rotary-Field phase shifter.

This paper discusses adaptation of Dual-Mode and Rotary-Field ferrite phase shifter types to include duplexing. From an ideal point of view, the duplexing would be represented by the functional block diagram of Fig. 3, consisting of a phase shifter separate from a four-port circulator having one port terminated. In actual implementations, the circulator and phase shifter overlap, so that the performance of the composite device as a duplexer may be affected by the phase shifter characteristics as well as by the behavior of the nonreciprocal element providing the circulator function.

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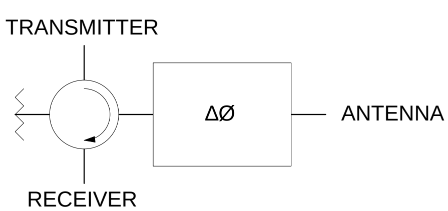
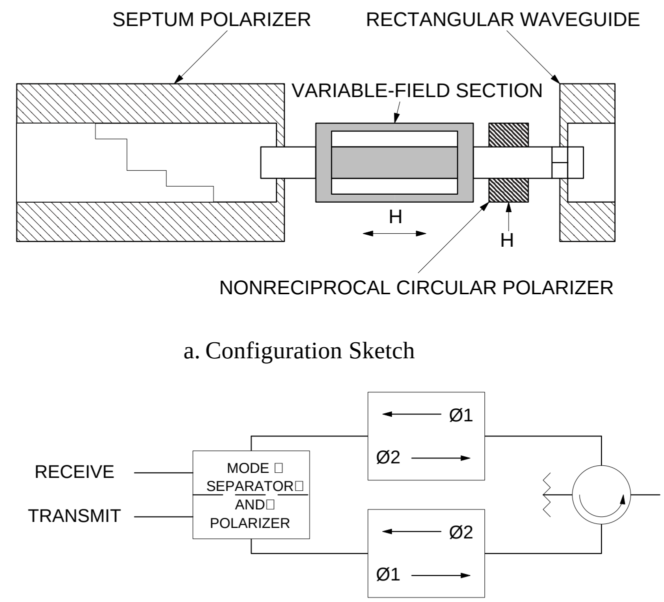


Fig. 3. Ideal duplexing reciprocal phase shifter block diagram.

II. Dual- Mode Phase Shifter Duplexing

One approach to duplexing of ferrite Dual-Mode phaseshifters is to substitute a reciprocal quarter-wave plate for the nonreciprocal type at the nominal input to the device. Then if, for example, a horizontal linearly polarized wave is incident on the (now reciprocal) quarter-wave plate in the transmit direction, the wave appearing at the same plane in the receive direction will be vertically polarized. The device input may then be matched to square waveguide and coupled to an orthogonal mode transducer to separate the transmit and receive waves. A more interesting approach, however, is to delete the input quarter-wave plate altogether, match the input to square waveguide, and couple to a septum polarizer. The septum polarizer combines the functions of mode separator and reciprocal circular polarizer/depolarizer into a single structure. Furthermore, the two single-mode waveguides at the input of the septum polarizer are adjacent, which may be advantageous from a packaging viewpoint. Fig. 4a presents a sketch showing the latter configuration.



a. Configuration Sketch

b. Block Diagram

Fig. 4 Duplexing Dual-Mode Phase Shifter Concept

Clearly, the four-port circulator behavior is provided by the nonreciprocal quarter-wave plate at the *output* of the device, and the appropriate functional block diagram is that of Fig. 4b rather than Fig. 3. In the absence of any effects of finite isolation of the septum polarizer, the circulator isolation I in dB. will depend on the magnitude of the deviation angle $\Delta\phi$ from the ideal 90 degree value of the differential phase of the nonreciprocal quarter-wave plate as follows:

$$I = -20 \log_{10} (\sin(\Delta\phi)/2). \quad (1)$$

This relationship is plotted in Fig. 5 for values of $\Delta\phi$ up to 30 degrees. From [5], a well-designed nonreciprocal quarter-wave plate should provide isolation values above 25 dB. over an 8 percent bandwidth, and above 20 dB. over a 16 percent bandwidth. Further degradation may occur as a result of finite isolation of the septum polarizer or mode conversion within the phase shifting region. The net isolation will be determined by the vector sum of the various error phasors at the ends of the device, and is likely to depend on the setting of the phase shifter section. Similar considerations apply to the case in which the reciprocal quarter-wave plate and orthogonal mode junction scheme is used. The block diagram of Fig. 4b is correct in the sense that error signals caused by finite isolation will be absorbed in the film termination in the transmit direction and will appear at the TRANSMIT port in the receive direction.

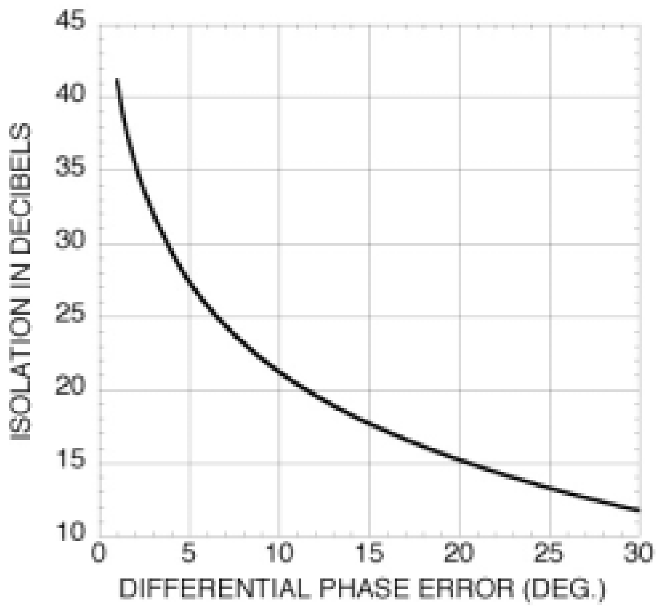


Fig. 5. Isolation Dependence on Phase Deviation from 90∞

Fig. 6 shows a photograph of an experimental duplexing Dual-Mode phase shifter operating at X-band and providing approximately 450 degrees of latching phase shift at laboratory ambient temperature.A commercially available septum polarizer is fastened to the square waveguide end of the test piece. An adapter is used to separate the adjacent rectangular waveguide outputs of the septum polarizer. Fig. 7 shows typical insertion loss and isolation data measured on this unit over the band 9.2 to 9.7 GHz. Both parameters were somewhat dependent on the phase shift setting, with the isolation degrading to a worst-case value of about 17 dB. for states near the reset end of the latching phase shift range.

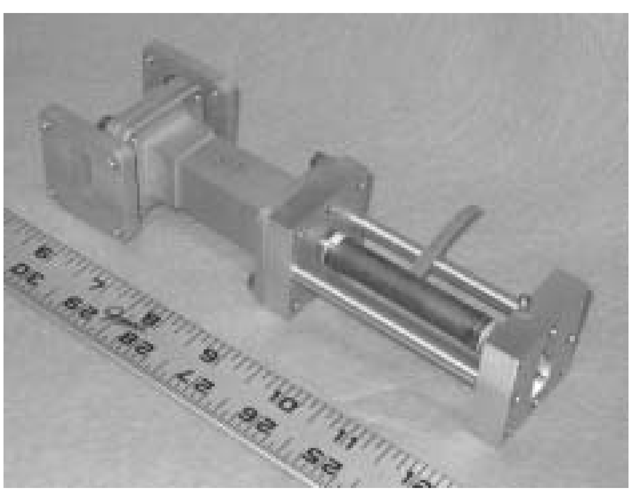


Fig. 6. Experimental Duplexing Dual-Mode Phase Shifter.

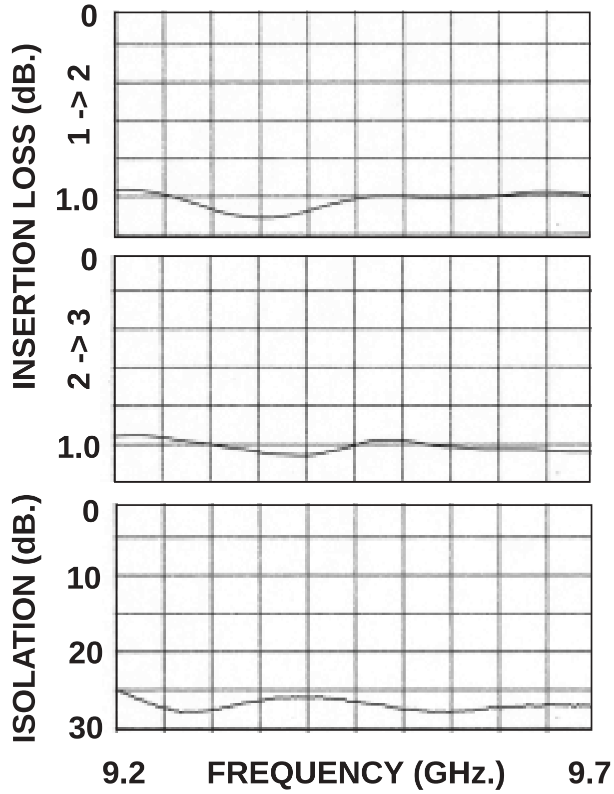


Fig. 7. Measured Data on Experimental Unit

III. Rotary-Field Phase Shifter Duplexing

Duplexing of ferrite Rotary-Field phase shifters is readily achieved by substituting a nonreciprocal quarter-wave plate for the reciprocal type at the nominal input to the device. As before, if a horizontal linearly polarized wave is incident on the (now nonreciprocal) quarter-wave plate in the transmit direction, the wave appearing at the same plane in the receive direction will be vertically polarized. The device input is then matched to square waveguide and coupled to an orthogonal mode transducer to separate the transmit and receive waves. Fig. 8 presents a block diagram showing the revised configuration.

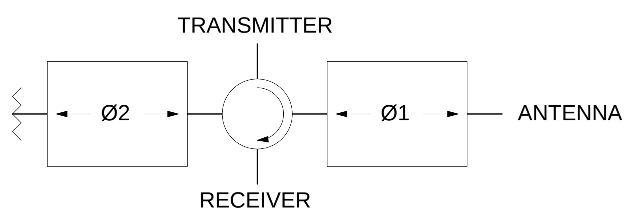


Fig. 8. Duplexing Rotary-Field Phase Shifter Equivalent Block Diagram.

This duplexing arrangement was first described more than thirty years ago [6] in connection with the high power Rotary-Field phase shifter that was then being developed for use in the USAF/ Westinghouse (now Northrop-Grumman) E-3 AWACS radar antenna, and is included here mainly for completeness. Although further changes were incorporated in the production version of the phase shifter, the basic duplexing principle remained the same. The phase shifter design was worked out by Microwave Applications Group (MAG) and several thousand units were manufactured by MAG and Westinghouse/Northrop Grumman. These units currently remain in service on E-3 AWACS radar systems.

As with the Dual-Mode case, isolation is limited first of all by the deviation of differential phase of the nonreciprocal quarter-wave plate from the ideal 90 degree value, and the relationships of (1) above and [5] will apply. Further degradation may occur because of deviations from ideal value of the differential phase of the ferrite half-wave plate or of the reciprocal quarter-wave plate at the output end of the device.

IV. Array Antenna Applications

Phased-array antennas with one-axis electronic scanning typically use one phase shifter per row or column of radiators, and planar arrays with two-axis electronic scanning typically use one phase shifter per radiating element. In the single-axis case with constrained (e.g. waveguide or other transmission line) feed, duplexing at the phase shifter level allows separate manifolds to be used for distributing transmitter power and for combining received signals. This permits, for example, uniform illumination to be used in transmitting, for smallest beamwidth and highest effective radiated power, while the receive direction might use amplitude weighting for sidelobe suppression. Another possibility is to add low-power phase shifters in the RECEIVE manifold to allow an offset beam pointing direction while both TRANSMIT and RECEIVE beams are being scanned by the duplexing phase shifters.

Building a constrained feed for a two-axis scanning planar array is already a challenge, especially at higher microwave frequencies, without piling on the requirement for *two* independent feeds for TRANSMIT and RECEIVE. However, an interesting possibility exists for the case of a space-fed phased-lens configuration. Such a lens can be populated with duplexing Dual-Mode reciprocal ferrite phase shifters that omit the nonreciprocal quarter-wave plate nearest to the feed side of the lens. The lens is then illuminated with one sense of circular polarization in the transmit direction, and will collimate the opposite sense of circular polarization in the receive direction for the same beam pointing direction. A septum polarizer driving the feed horn (or a septum polarizer in each horn for the case of a cluster) completes the duplexing function. That is, one rectangular waveguide port of the septum polarizer is used for TRANSMIT, and the RECEIVE signal appears at the other waveguide port. The sketch of Fig. 9 illustrates this configuration.

A similar feed arrangement has been reported [7] for a phased-lens that transmitted one sense of circular polarization and received the opposite sense. In that case the ferrite elements

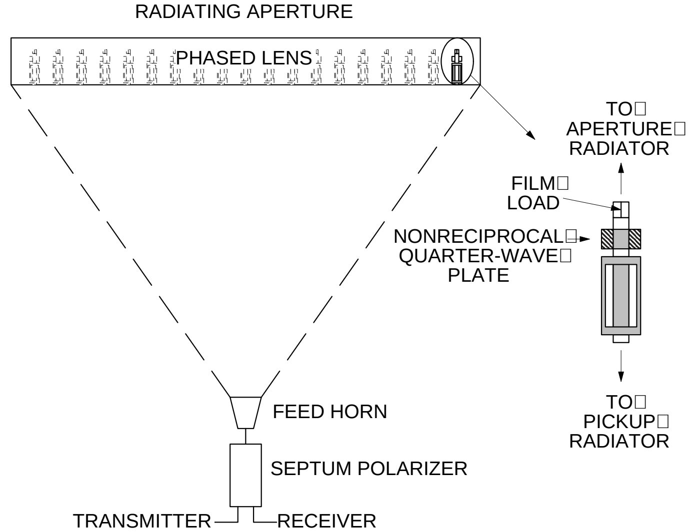


Fig. 9. Space-fed Duplexing Reciprocal Phased-Lens Sketch

had no nonreciprocal quarter-wave plates and no film loads. The reciprocal phased lens described here allows the use of an electrically small feed horn (or horn cluster) and a small F/D ratio even though the horn radiation patterns parallel and perpendicular to the electric vector will be different at the extreme angles relative to broadside. The net effect will be a small increase of insertion loss at those angles. In conclusion, the duplexing phased-lens is unusual because removing a large number of items (the rear nonreciprocal quarter-wave plate for each element) actually improves the performance and functionality of the overall system.

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