III-8 POLARIZATION INSENSITIVE PHASE SHIFTER FOR USE IN PHASED ARRAY ANTENNAS

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Theory of Operation - The theory of operation of a non-reciprocal circularly polarized (CP) phase shifter has been described in a paper by the authors[1], and the PIP device is simply a modification. The CP phaser can be converted into a PIP device through the modification indicated in Figure 1.

A second ferrite rod is placed in tandem with respect to the first, and a coil is wrapped around the second rod in the opposite direction so that the internal magnetization of the second rod opposes that of the first. Since the magnetic fields are reversed for the two rods, the phase-current characteristics for each rod are mirror images. For a given positive value of coil current (I_o) and right-handed circular polarization input, rod No. 2 delivers a phase delay of ϕ_2, and rod No. 1 delivers a phase advance of ϕ_1. The total reciprocal phase shift through the device is, therefore, a phase delay of $\phi = |\phi_2| - |\phi_1|$. If left-handed circular polarization were applied to the phase shifter instead of right-handed, the first rod would give a phase delay, and the second would give a phase advance for the same direction of coil current. In other words, the roles of the two rods would be reversed, but the phase shift through the device would still be a phase delay of ϕ.

A PIP device similar to that discussed above was presented in a paper by H. Scharfman[2], however, that device was extremely inefficient because of the choice of ferrite material.

Another version of the PIP is illustrated in Figure 2(a). In this transmission PIP, a polarization inverter or half-wave plate is inserted between the two ferrite rods, and the winding direction of both coils is the same. As a result, the internal magnetic fields shown in each rod are in the same direction, and when right-handed circular polarization is applied to the phase shifter, left-handed circular polarization will emerge. The phase-current characteristics of this phaser are the same as those shown in Figure 1. The phase shift in rod No. 2 is the same as it was in Figure 1, since both the magnetic field and the RF circular polarization through the rod have been reversed.

The reflection type PIP shown in Figure 2 (b) may be developed from the transmission device by bisecting the half-wave plate with a conducting plane. If right-handed circular polarization is applied to the device, right-handed circular polarization will emerge delayed in phase. Figure 3 is a photograph of two prototype reflection type PIP phase shifters, one complete, and one from which the ferrite rod, dielectric quarter-wave plate, shield, and radiating element have been removed for a component view.

DESIGN PARAMETERS AND LIMITATIONS

In general, the initial microwave permeability, (μ), is assumed to be equal to unity, whereas, it actually may range between zero and one depending upon the value of the normalized saturation magnetization,

$$p = \frac{\gamma e\, 4\pi Ms}{\omega} = \frac{\omega_m}{\omega}$$

where γ_e is the gyromagnetic ratio, M_s is the saturation magnetization, and ω is the angular radian frequency. Figure 4 is a plot of the initial permeability as a function of the mormalized saturation magnetization. This result is purely empirical and approximate, but it will help to illustrate the basic design considerations of the PIP. As the initial permeability is lowered toward zero, the asymmetry of the phase-current characteristic (illustrated in Figure 1) becomes more pronounced, and more reciprocal phase shift is obtained[3]. Therefore, the basic procedure for optimizing a PIP phase shifter design begins by choosing a ferrite material which will give the highest value of normalized saturation magnetization (p), without introducing excessive losses. This value is usually about 0.9, although peak power requirements may cause it to be reduced. Other constraints, such as size, weight, and drive power will determine the particular waveguide configuration to be used.

EXPERIMENTAL RESULTS

Figure 5 is a compilation of the performance parameters of an actual PIP device designed and tested at Raytheon.

Figure 5. Phaser Performance Summary

Phase Range	360 deg
Frequency Range	K_u-band ± 5%
Insertion Loss	1.1 db
Peak Power	250 watts
Average Power	3 watts
Temperature Sensitivity (Insertion Phase)	2.8 deg/°C
Coil Parameters	
Maximum Switching Energy (360 deg)	175 micro joules
Maximum Hold Power (360 deg)	0.33 watt
Maximum Current (360 deg)	90 MA
Inductance	51 mh
Resistance	40 ohm
Number of Turns	1800
Switching Speed	50 microsec
Phase Error	
Insertion Phase Reproducibility	9 deg RMS
ϕ-I Non-linearity	30 deg max
Element Weight (exclusive drive circuit)	0.75 oz.

Figure 6 shows four measured phase-current curves for the four possible polarization input signals at midband. The dotted line in each of the four curves is the characteristic of the linear drive amplifier that drives each phase shifter and the solid lines are the measured curves. The deviation of these curves from the dotted straight line represents the error the phase shifter would present when operating in an array. The maximum hysteresis loop width is less than 20 degrees and occurs in the region of 60 ma. coil current. The maxium deviation of the curve from linear for all polarizations is about 30 degrees excluding hysteresis.

The phase-current characteristic of the ferrite phase shifter changes slope with frequency at a rate of one percent bandwidth.

The maximum peak power capability of the phaser is limited by the onset of ferrite material loss non-linearities which occur at a discrete power level.[4] Above this peak power threshold, the device insertion loss rises sharply. The peak power threshold is independent of the applied field over the usable phase range.

The maximum hold power for any phase shifter is required when it operates at maximum coil current, which corresponds to 360 degrees of phase shift. The maximum hold power of 0.33 watt is determined by the coil volume available between the waveguide diameter and the magnetic shield of the beam steering element; the smaller the coil volume, the larger the hold power required. This coil volume is restricted indirectly by the maximum antenna scan angles which in turn limit the center-to-center spacing of the beam steering elements. The maximum switching energy can be calculated from the equation,

$$W_m = 1/2LI^2$$

The energy required to switch between the zero phase state (I = 8 ma.) and the maximum phase state (I = 90 ma.) is 175 micro joules.

References

1. MC. Mohr and S.R. Monaghan, "A Circularly Polarized Phase Shifter for Use in Phased Array Antennas", G-MTT December 1966, pps.
2. H. Scharfman, "Three New Ferrite Phase Shifters", Proc. IRE, Oct. 1956, pps. 1456-1459.
3. R.C. LeCraw and E.G. Spencer, "Tensor Permeabilities of Ferrites Below Magnetic Saturation", IRE Convention Record, Vol. 4, Part E, 1956, pps. 66-74.
4. B. Lax and K. Button, Microwave Ferrites and Ferrimagnetics, Ch. 5, McGraw Hill, 1962.

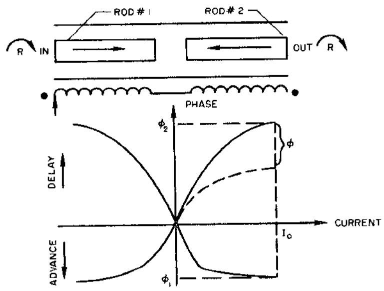

FIG. 1 - Transmission PIP Phase-Current Characteristic

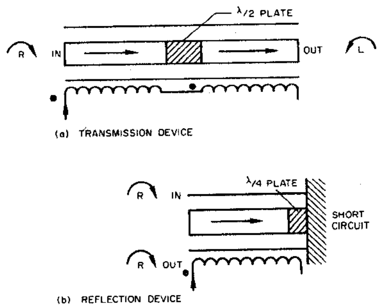

FIG. 2 - PIP Phasers

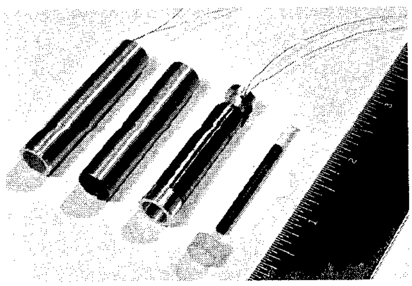

FIG. 3 - Prototype PIP Phaser

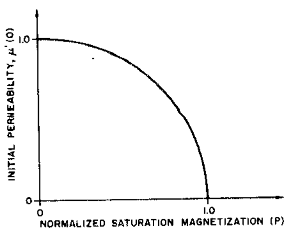

FIG. 4 - Initial Permeability vs Normalized Saturation Magnetization

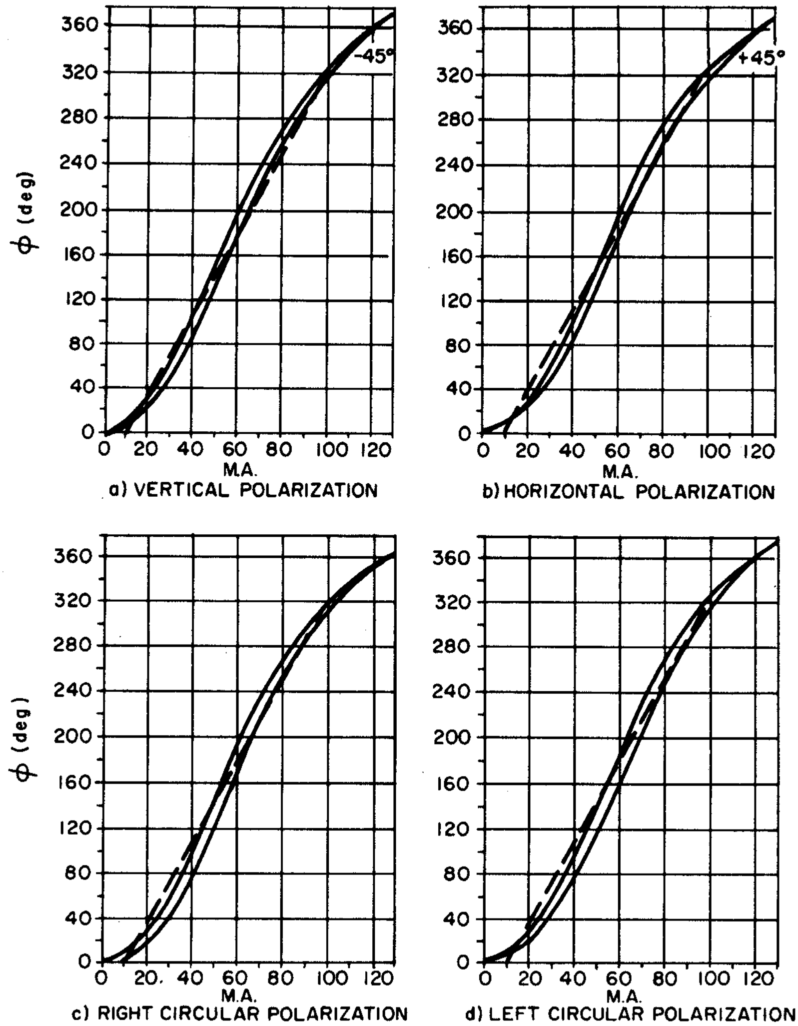

FIG. 6 - Phase Current Characteristics for all Polarizations at Midband