A Low-Cost Construction Technique for Garnet and Lithium-Ferrite Phase Shifters

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Abstract—**Low-cost construction techniques for S-band twin-slab ferrite phase shifters are presented along with an experimental comparison of garnet and lithium-ferrite materials. A 3-bit phase shifter with lithium-ferrite material, which is approximately half the price of garnet material, had a measured loss of 0.4 dB and a peak power handling of 4.5 kW.**

INTRODUCTION

RECENT EFFORTS in the development of twin-slab ferrite phase shifters have emphasized fabrication simplicity to reduce production cost [1]–[3]. A new technique, which is described in this paper, demonstrates that nonprecision parts and low-cost magnetic materials can be used without degrading phase-shifter performance.

The nonreciprocal latching ferrite phase shifters in this paper are all assembled with the foil-wrapped construction technique. Data are presented for analog and digital garnet phasers and for analog and digital lithium-ferrite phasers. The analog devices utilize flux drive while the digital devices use saturation drive.

PHASE-SHIFTER CONSTRUCTION

In addition to being low cost, the phase-shifter construction must exhibit the following requirements to obtain good RF performance.

1) Minimum gap between toroid and waveguide broadwalls—an air- or epoxy-filled gap between the toroid and the waveguide broadwalls serves as a launching mechanism for higher order modes which in turn cause insertion-loss spikes at resonant frequencies.

2) Minimum pressure exerted on toroid—the pressure that the structure exerts on the toroid must be minimized, especially with garnet materials, to avoid magnetostrictive effects [4].

3) Thermal design—the thermal design must be adequate to handle the average power requirement of the phase shifter.

One construction technique which satisfies all of the above requirements is the foil-wrapped approach shown in Figs. 1 and 2. In this approach, the toroid is sandwiched between two low-dielectric-constant slabs and wrapped with a thin copper foil. The dielectric slabs contain a resistive-film mode suppressor to insure the suppression of higher order mode resonances [5]. Two methods have been used for bonding the foil to the ferrite. The first uses a thin adhesive which maintains good adhesion with less than a 1-mil bond thickness. In the second method, the ferrite toroid is plated along the top and bottom surfaces shown in Fig. 1 and then soldered to the foil. This technique forms a very good bond without sacrificing performance. The foil-wrapped unit is then inserted into a loose-tolerance housing (Fig. 2) which provides the mechanical strength, the flanges, and the cooling springs. The cooling springs can either be used as air fins or as a conducting path to a cold plate. To

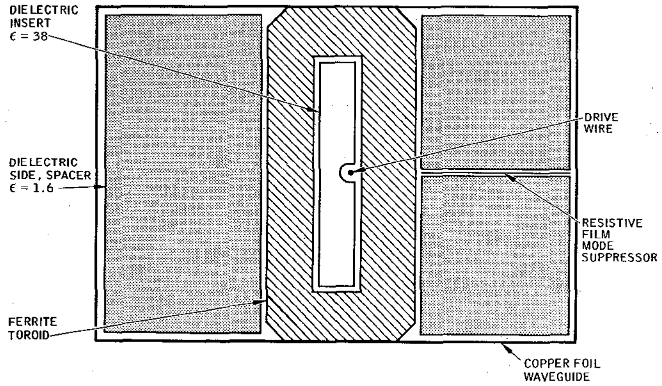

Fig. 1. Phase-shifter cross section.

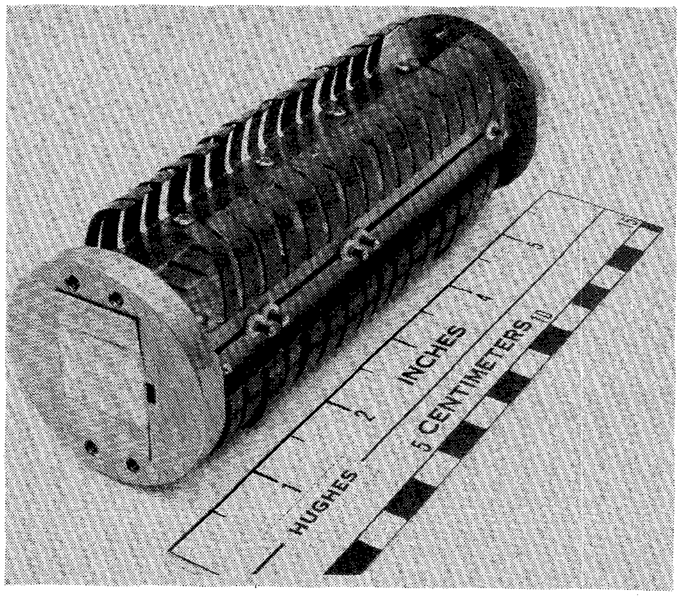

Fig. 2. 3-bit foil-wrapped phase shifter.

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further reduce cost, the toroid used in this phase shifter is an "as-fired" toroid, i.e., no machining operation is required on the toroid except to cut it to the proper length. With this construction technique, the thin foil will make good contact with the toroid, in spite of the irregularities of the toroid surface.

PERFORMANCE

The phase-shifter performance using a flux-driven garnet toroid (Table I) with the foil-wrapped construction is shown in Figs. 3–7. The insertion loss (Fig. 3) with either the adhesive or solder bond is less than 0.5 dB over a 20-percent bandwidth. This loss does not include the loss of the transitions. The matching transitions are four-section dielectrically loaded Chebyshev transformers which match the phase shifter to WR-284 waveguide. The insertion loss of these transitions are 0.05 dB each.

The insertion phase varies only slightly over the operating temperature range (Fig. 5). This is very important in systems with high-amplitude tapers across the array in order to minimize temperature-induced systematic phase errors. The explanation for this temperature insensitivity is that the two permeability components, μ' and κ', which control the phase, change in such a way as to compensate each other as the saturation moment ($4\pi M_s$) decreases with temperature. The diagonal component μ' increases asymptotically toward 1 and the off-diagonal component κ' decreases linearly toward 0 as $4\pi M_s$ decreases to 0. These curves can be seen in [6]. The particular temperature at which the phase flattens depends on the material, the RF frequency, and the phase-shifter geometry.

It is also significant to note that the critical peak power level of a ferrite phase shifter (Fig. 7) which sees a 3:1 mismatch (the level it might expect to see in an array) is only about 20 percent lower than the same phase shifter

TABLE I
FERRITE MATERIAL PARAMETERS

	GARNET	LITHIUM FERRITE
Saturation Moment ($4\pi M_s$) - Gauss	686	770
Remanent Magnetization (B_r) Gauss	480	580
Coercive Force (H_c) Oersteds	0.8	1.0
Dielectric Costant (ϵ')	14.6	19.1
B_r Temperature Sensitivity (%/°C)	0.29	0.49

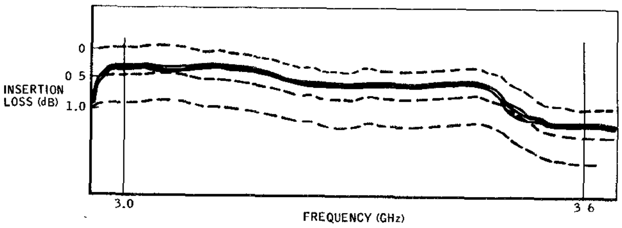

Fig. 3. Garnet phase-shifter insertion loss.

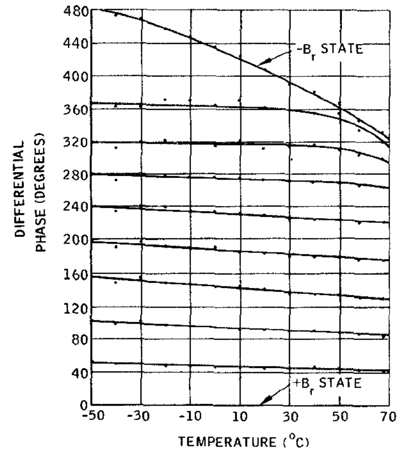

Fig. 4. Differential phase versus temperature for garnet phase-shifter with flux drive.

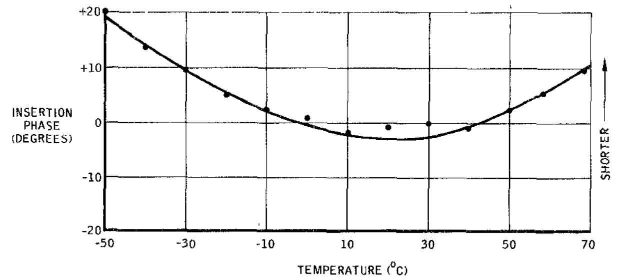

Fig. 5. Insertion phase versus temperature for garnet phase shifter.

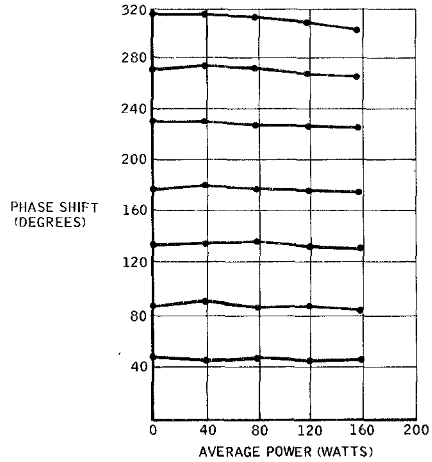

Fig. 6. Garnet phase-shifter average power performance with flux drive.

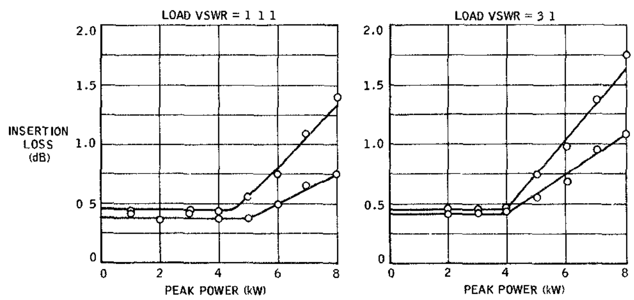

Fig. 7. Garnet phase-shifter peak power performance for matched and unmatched load conditions.

TABLE II
PHASE-SHIFTER PARAMETERS

	GARNET	LITHIUM FERRITE
Figure of Merit Degrees/dB	1000	770
Phase Shift per Inch - Degrees/Inch	82	95
Peak Power Handling - kW	5.0	4.5
Phase Shift Temperature Sensitivity with Digital Drive - %/°C	0.37	0.65
Switching Time (180° Bit) μsec	2.0	2.0
Switching Energy (180° Bit) μjoules	48	56

followed by a matched load. One might expect that with a 3:1 mismatch the critical power level should have dropped by 50 percent as in diode phase shifters; however, because of the distributed nature and the nonreciprocal nature of ferrite phase shifters, the performance under a high mismatch was better than originally anticipated.

The nonreciprocal nature of this phase shifter is such that for one direction of power flow, the fields are concentrated in the toroid center and for the reverse direction the fields are concentrated along the side of the toroid. Therefore, when power is flowing simultaneously in both directions due to an impedance mismatch, the peak fields are not as high as if the device were reciprocal.

Twenty 3-bit garnet phase shifters with approximately the same geometry and the same material as the analog phase shifter were also assembled with the preceding construction technique. The material came from three different batches and the bit lengths were the same for all the phase shifters. The average insertion loss for the 20 units over a 10-percent frequency band and eight phase states was 0.44 dB and the highest loss was 0.78 dB. The rms phase error for the 20 units was 7.23° at room temperature. This includes the insertion phase error. A summary of the phase-shifter performance is shown in Table II.

LITHIUM-FERRITE MATERIAL

In a further effort to reduce phase-shifter costs, lithium-ferrite materials were investigated [7]. Due to the absence of rare-earth doping, these materials are about half the cost of the garnets. One Ampex lithium-ferrite material (Table I) showed exceptional microwave performance in a 3-bit phase shifter (Figs. 8–12) and excellent switching characteristics (Table II). Five foil-wrapped digital phase shifters were assembled utilizing two batches of this material. The phase repeatability was extremely accurate

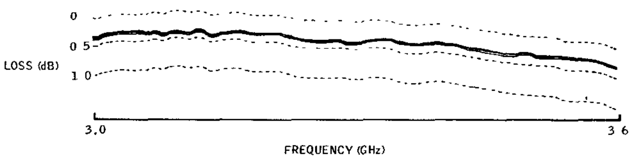

Fig. 8. 3-bit lithium-ferrite phase-shifter insertion loss.

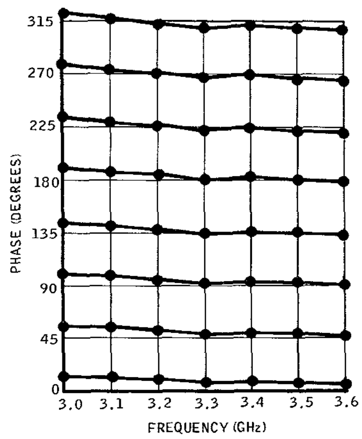

Fig. 9. 3-bit lithium-ferrite phase shifter. Phase versus frequency.

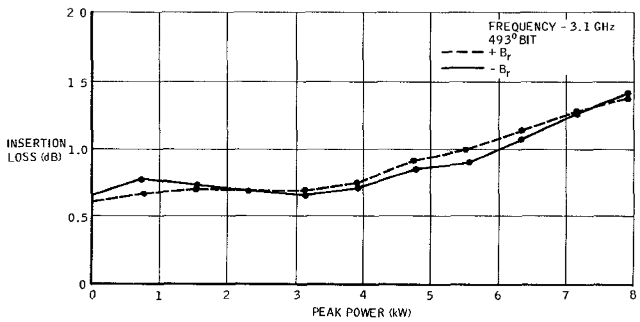

Fig. 10. Lithium-ferrite phase-shifter peak power performance.

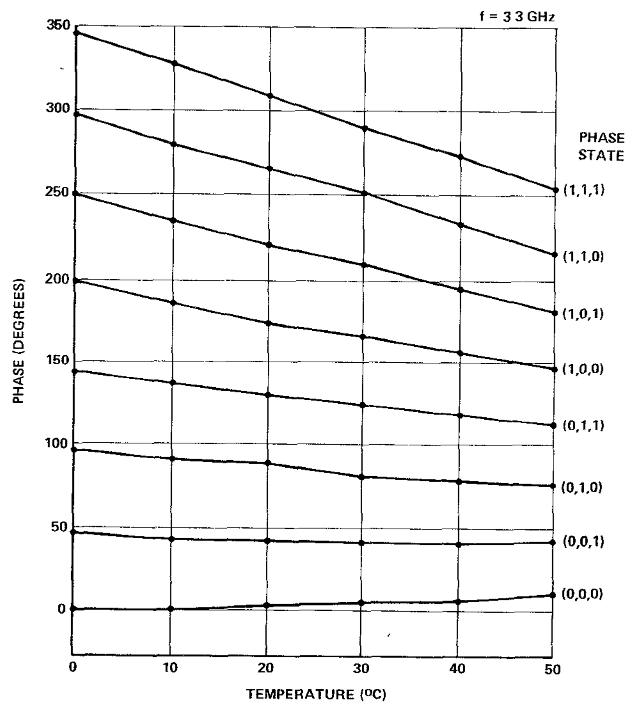

Fig. 11. Lithium-ferrite phase shifter. Phase versus temperature with digital drive (the 0,0,0, phase state represents the insertion phase).

(±1.8 percent) and the magnetostrictive effects were also much less noticeable than with the garnets. The peak power handling shown in Fig. 10 is equivalent to that of

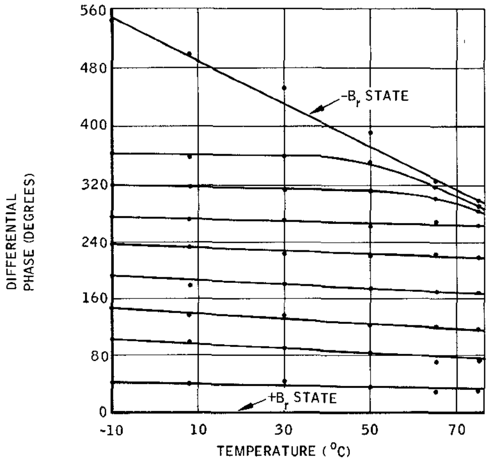

Fig. 12. Lithium-ferrite phase shifter. Differential phase versus temperature with flux drive.

the garnet. The only significant disadvantage to this lithium-ferrite material is that its temperature sensitivity (Fig. 11) is almost twice as high as garnets. With flux drive, however, very good temperature stability can be obtained over wide temperature ranges, as shown in Fig. 12.

CONCLUSIONS

For S-band phased-array applications of moderate element power ($\leq$5-kW peak), the foil-wrapped lithium-ferrite phase shifter with flux drive is an excellent choice with superior performance at low cost.

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Practical Aspects of Phase-Shifter and Driver Design for a Tactical Multifunction Phased-Array Radar System

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***Abstract*—Three microwave garnet phase-shifter designs are used in the AEGIS weapons system. The microwave design is straightforward except that the toroid assembly is potted with silicone rubber to increase its power-handling capability and the magnetizing wires are shielded with a spiral-wrapped wire to prevent the propagation of higher order modes. The driver circuit uses a new "flux-feedback" concept for improved accuracy and employs monolithic circuits, hybrid circuits, and discrete components. Mechanical and electrical design of the interfaces with mating components are important cost considerations and the chosen designs are described in detail. Several techniques for improving production yield are discussed and a table of production statistics is provided. Performance histograns and data averages as a function of time and operating frequency are also presented.**

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INTRODUCTION

THE DESIGN and production of phase shifters and drivers for a large tactical phased array involves the resolution of a matrix of technical and economic problems. For the AN/SPY-1 array the requirements for a viable design include low unit cost and high production yield; high phase accuracy with respect to manufacturing spread, operating environment, and long-term drift effects; small size and weight; ruggedness and reliability for shipboard environment including conformance with military specifications; on-line monitoring; and compatible interface with a multifunction radar system. This combination of requirements has been met in the designs to be described. The