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A 60 GHz DUAL-MODE FERRITE PHASE SHIFTER

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Introduction

Projected system needs continue to indicate a future requirement for phase shifters at millimeter-wave frequencies. The current state-of-the-art at these frequencies clearly favors ferrite type phase shifters over competing approaches. The two geometries that have been mainly considered for latching ferrite units are: (a) the axial toroid, transverse bias field, nonreciprocal type, and, (b) the dual-mode, longitudinal bias field, reciprocal type. The dual-mode type has a very simple r-f waveguide cross-section compared with the axial toroid type, and thus offers the possibility of easier and cheaper fabrication to necessary tolerances compared with the axial toroid type.

Computational results also indicate that the dual-mode type may be capable of operating at lower insertion loss levels than the axial toroid type at millimeter-wave frequencies, at least under certain assumptions. The phenomenon occurs when magnetic activity of the ferrite is relatively low, i.e. saturation magnetization is limited to a value giving small ω_M/ω ratios. In this case insertion loss is dominated by waveguide wall losses, which are greater for the axial toroid because of current concentration adjacent to the limited region of high dielectric loading. Figure 1 shows a plot of predicted comparative losses for axial toroid and dual-mode phase shifters, each using materials with $4\pi M_s$=3000 Gauss, in the 20 to 100 GHz region.

This paper presents the results obtained from an investigation of the feasibility of constructing a dual-mode, latching, reciprocal ferrite phase shifter designed to operate in the 60 GHz frequency region. Design considerations, problems, experimental data, and future prospects are discussed.

Design Considerations

The first millimeter-wave dual-mode, latching ferrite phase shifter was described[1] at the 1971 IEEE GMTT International Microwave Symposium. This unit operated at 35 GHz and produced 360 degrees of latching phase shift with a base insertion loss level of about 1.7 dB. The material used was a 5000 Gauss Ni-Zn ferrite with a low remanence ratio.

Very significant improvements have been made in the design of dual-mode phase shifters in the past eleven years, including units operating at 35 GHz. Phase shifters currently being produced for system application in that frequency region now exhibit base insertion loss levels on the order of 1.0 dB for a latching phase shift range of 430 degrees. These same design improvements were incorporated into the experimental 60 GHz phase shifter.

A Mg-Mn ferrite of 3000 Gauss saturation moment was used for the 60 GHz design. While the magnetic activity is less than that of Ni-Zn or some lithium ferrites, this material has good square-loop properties plus low dielectric losses and a lower dielectric constant than the lithium material. The net result is reduced conductive and dielectric losses, with a larger ferrite rod diameter.

A thorough investigation and discussion of design considerations for the dual-mode phase shifter exists in the literature.[2,3,4] One significant conclusion is that a round rod geometry permits operation at larger cross-sections than a square rod geometry without introducing unavoidable spurious-mode responses (TE_{11} mode in square guide versus TE_{21} mode in circular). For this reason a circular rod of 1.57 mm. (.062 inch) diameter was chosen for the r-f ferrite waveguide.

Magnet design for the 60 GHz phase shifter nonreciprocal polarizers was based on similar designs currently used at 35 GHz and lower frequencies. Because the rod diameter is substantially smaller than for lower frequencies, setting up the desired transverse fourpole field is more difficult. By minimizing air gaps between the magnet surfaces and the rod surface, polarizer length was held to about the same value as the 35 GHz design using the same materials.

Ferrite yokes forming the return path for the remanent flux in the variable-phase section were formed as a pair of "half cylinders" with lapped bearing surfaces to contact the rod at each end. This curved-surface geometry is considerably less susceptible to breakage in handling than a flat surface yoke. A switching coil having 100 turns of 35 gauge wire was fitted around the center rod within the "window" of the yoke return paths. The rod itself was, of course, metallized with a thin sputtered conductive film.

Experimental Results

Tests were carried out on a few experimental samples to verify the anticipated performance characteristics. Different test setups were used for measurement of phase and amplitude. Phase data were measured on a waveguide bridge, balancing the insertion phase of the test arm by adjustment of a mechanical phase shifter in the reference

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arm until a null was detected at the summing point. Amplitude data were measured using a pair of directional couplers in a ratio meter setup. The millimeter-wave source was a mechanically tunable klystron, necessitating the laborious taking of point-by-point measurements in frequency.

Performance of the polarizer magnets was first evaluated using a rod test piece. Differential phase shift for the magnets, as initially magnetized, was found to be on the order of 100 to 104 degrees over the 3 GHz band from 60 to 63 GHz. Variation of the differential phase shift with frequency followed the expected monotonic decrease with increasing frequency, indicating reasonable match of the test rod to the mating waveguides.

Considerable difficulty arose out of attempts to make a good impedance match between the ferrite rod assembly and the mating waveguides. At lower frequencies, it is customary to achieve good match by bonding a dielectric piece to each end of the ferrite and allowing this dielectric "plug" to extend some distance along the axis of the coupling waveguide. The length and diameter of the dielectric section are adjusted to give the effect of a quarter-wave transmission line transformer.

The tiny size of the parts for the 60 GHz design did not permit accurate forming of the dielectric step transformer arrangement. Instead, several varieties of tapered transformers were investigated. One variety used a "screwdriver blade" wedge-type taper, with the tip of the wedge tried in positions parallel and perpendicular to the waveguide broad walls. Another geometry was that of a full conical taper. The full conical taper appeared to give adequate results.

Figures 2 through 5 show plots of data measured on the best test unit constructed. The insertion loss was measured, at a number of phase settings, at 60, 61, 62 and 63 GHz. The maximum and minimum values measured are plotted in Figure 2 and an "envelope" sketched. The base loss level of 1.5 dB recorded compares favorably with theoretical expectations and with any known published results on alternate latching ferrite phase shift geometries at this frequency range. Figure 3 shows a similar "envelope" of return loss values for the same unit. It is clear that the rise of insertion loss at the low end of the measured band can be attributed to mismatch. Figure 4 summarizes phase shift data measured with a sequence of steady drive current values tracing out a hysteresis characteristic. While the maximum phase shift is close to the theoretically predicted value, the latching phase shift range of 363 degrees is reduced below the potential amount because the major-loop remanent points are below the "knees" of the curve. This behavior suggests that the effective air gap between the return path yokes and the ferrite rod is larger than desirable. Possible remedies would be to polish the rod and yoke contact surfaces, and/or increase the contact area.

Switching characteristics were in the expected range and are illustrated in the oscilloscope trace photograph of Figure 5. This photograph shows "full set" and "full reset" pulses superimposed. The drive voltage for these pulses was 15 volts, with the indicated time for settling of transients on the order of 12 microseconds. Average current during these pulses was about 300 milliamperes. Finally, Figure 6 shows a photograph of the 60 GHz unit in its housing.

Conclusions

The data presented in this paper show that it is possible to build "conventional" dual-mode type ferrite phase shifters at 60 GHz with reasonable performance characteristics. In principal, the design could be scaled to yield a 94 GHz model, but several considerations may raise difficulties:

A. The ferrite rod transverse dimension will be on the order of 0.025 - 0.035 inch, while the rod length will be on the order of one inch. This "ferrite toothpick" would be very fragile without additional support during fabrication as well as in field use.

B. The yoke elements symmetrically placed around a ferrite rod to provide a closed magnetic path would have even smaller cross-sectional dimensions, further aggravating the handling problem.

C. The nonreciprocal polarizers at each end of the latching phase shift section are formed using bias magnets to produce a transverse quadrupole field in the rod, over an appropriate length. The requirements on bias magnets are that the field intensity must be increased while the rod size decreases with frequency.

In fact, this set of potential problems is the same set that was of concern for the 60 GHz design. The success at 60 GHz lends some hope that the technique might be workable at 94 GHz, in which case a unit with base loss on the order of 2.5 dβ should be possible. On the other hand, the practical limits of fabricating units with even smaller cross-sectional dimensions must eventually set an upper bound to the frequency region for this class of phase shifter. Achieving an operating unit at 60 GHz reduces, but does not eliminate, risk in applying the approach at 94 GHz.

Acknowledgement

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References

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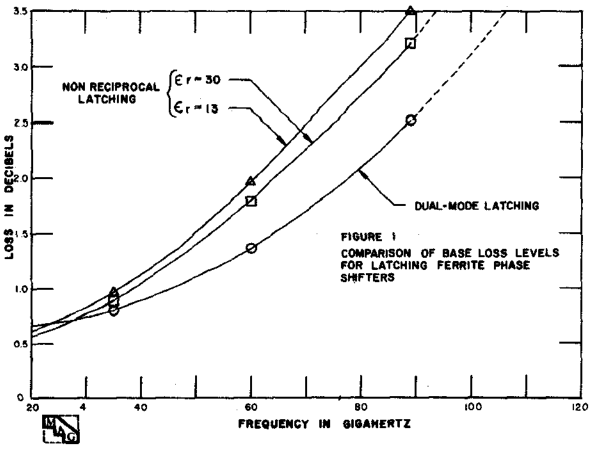
2. C. R. Boyd, Jr., "A Dual-Mode Latching Reciprocal Ferrite Phase Shifter", IEEE Trans. Microwave Theory and Techniques", Vol. MTT-18, pp. 1119-1124; Dec. 1970.

3. C. R. Boyd, Jr., "Comments on the Design and Manufacture of Dual-Mode Reciprocal Latching Ferrite Phase Shifters", IEEE Trans. on Microwave Theory and Techniques, Vol, MTT-22, pp. 593-601; June 1974.



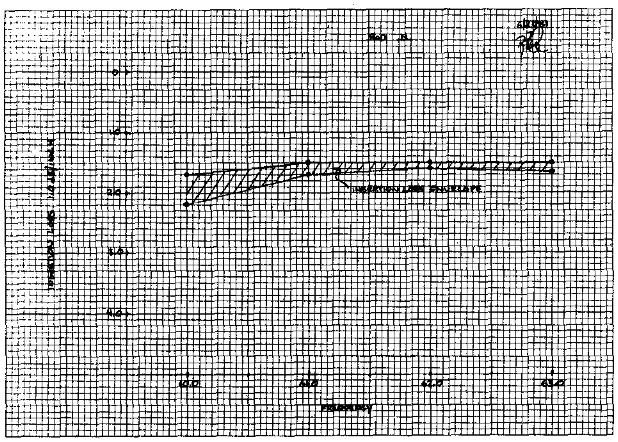


Figure 2 - Insertion Loss Data

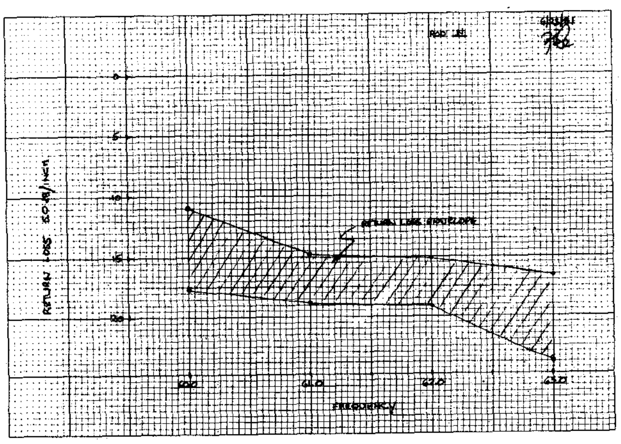


Figure 3 - Return Loss Data

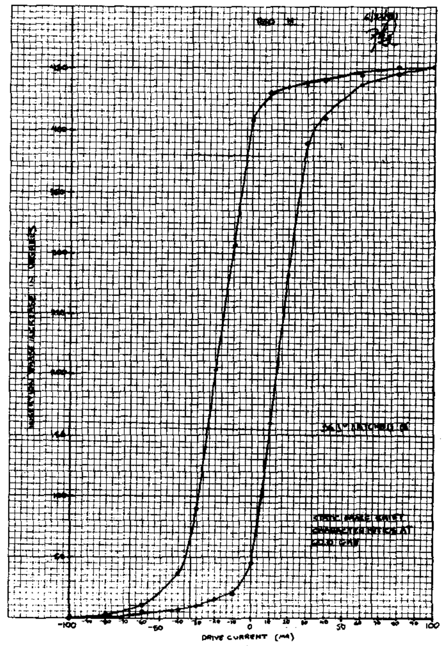
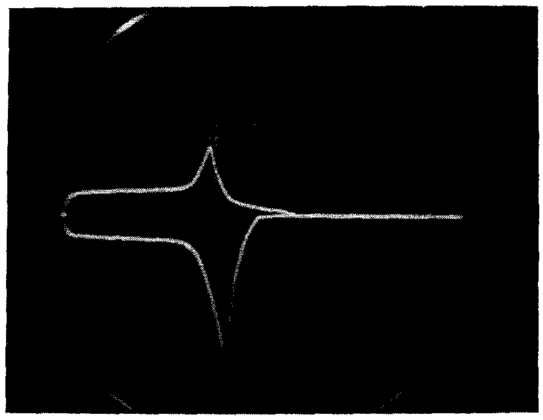


Figure 4 - Static Phase Shift Characteristics at 60 GHz



500ma/div.

2μsec/div.

Figure 5 - Switching Characteristics at 15 Volts Drive

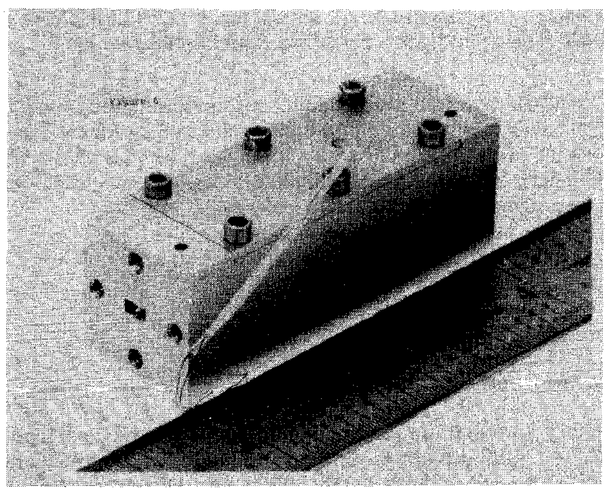


Figure 6 - Photograph of 60 GHz Phase Shifter