CONCLUSIONS

It has been shown that in partially dielectric loaded strip transmission line the microwave magnetic field was elliptically polarized at the air-dielectric interface. The degree of elliptical polarization was a function of the dielectric constant, the degree of loading, and the frequency. An expression relating these quantities has been derived. For specific values of dielectric constant and loading, the polarization factor at the dielectric surface was shown to be 1.2 or less over very broad frequency bands. Measurements in ferrite loaded strip transmission line and coaxial structures indicated the existence of a high sense of circularity at the dielectric interface over at least a 3 to 1 band. It is clear from the foregoing analysis and measurements that dielectric loaded strip transmission line and coaxial line are very well suited for broad-band nonreciprocal ferrite applications.

ACKNOWLEDGMENT

The authors are indebted to B. J. Duncan for suggesting the analysis presented in this paper and to L. Swern for his advice during the course of this work.

Ferrite Phase Shifter for the UHF Region*

C. M. JOHNSON†

Summary—**An extremely compact, low-loss, ferrite phase shifter has been developed for the 200 to 800-mc region. It consists of a folded stripline structure approximately 6½ inches long and less than 1 inch square in cross section. The device requires a longitudinal magnetic field of sufficient intensity to place the operating region above resonance. For field swings of about 900 oersteds (from 430 to 1250 oersteds at 400 mc), 360° change in phase shift can be obtained with about 1 db of loss. The phase shifter is reciprocal and shows identical low-power and high-power characteristics up to at least 10-kw peak. Some additional data are included on the operation of the phase shifter down to 10 mc and up to 2000 mc.**

INTRODUCTION

SEVERAL different types of electronically controllable ferrite phase shifters have been successfully developed for the microwave region. In the UHF region, however, ferrite devices capable of 360° phase shift have usually proven too lossy and bulky to be practical.

In an attempt to overcome these difficulties in the UHF region, a compact, folded stripline, ferrite phase shifter has been developed which produces 360° change in phase shift with very low loss over an extremely wide frequency region.

This phase shifter is operated on the high-field side of resonance, requiring a relatively large magnetic field. In compensation, however, operation in this region eliminates the nonlinear effects usually observed at high RF power levels. This characteristic, along with the fact that the phase shifter is reciprocal, permits its use in both transmitting and receiving systems.

DESCRIPTION

Construction

Fig. 1 shows the phase shifter construction. The device is about 6½ inches long and consists of 5 layers of stripline. Each layer is loaded with two 0.40-inch × 0.05-inch × 6-inch strips of ferrite, one on each side of the center conductor. The center conductor is folded as shown to provide continuity between layers. Thus, the total length of ferrite through which the wave must travel is 32.2 inches, or 82 cm.

Fig. 2 shows a photograph of the complete phase shifter. Input and output lines are standard RG-8/U cables. The transition to stripline is made simply by slotting the center conductor of the coax to receive the rectangular center conductor of the stripline and connecting the coax shield to the stripline ground plates.

In the model shown here the layers of stripline are fastened together by bolts spaced along the sides. These bolts also serve as electrical shorts between the ground plates.

The dimensions of the stripline shown in Fig. 1 are such that

$$\sqrt{\frac{\epsilon_1}{\mu_1}} \qquad Z_0 = 115 \text{ ohms},$$

where Z_0 is the characteristic impedance, ϵ_1 the relative dielectric constant, and μ_1 the relative permeability. For $\epsilon_1 = 11.5$ and $\mu_1 \approx 2$, typical of the ferrite material used, Z_0 is approximately 50 ohms. The permeability, of course, is a variable here, and therefore it is not possible to attain an exact 50-ohm impedance over the full range of phase shift.

---

* Manuscript received by the PGMTT, June 2, 1958; revised manuscript received, August 20, 1958. This research was supported by the AF Cambridge Res. Center under Contract No. AF 19(604)-2407.

† Electronic Communications, Inc., Timonium, Md.

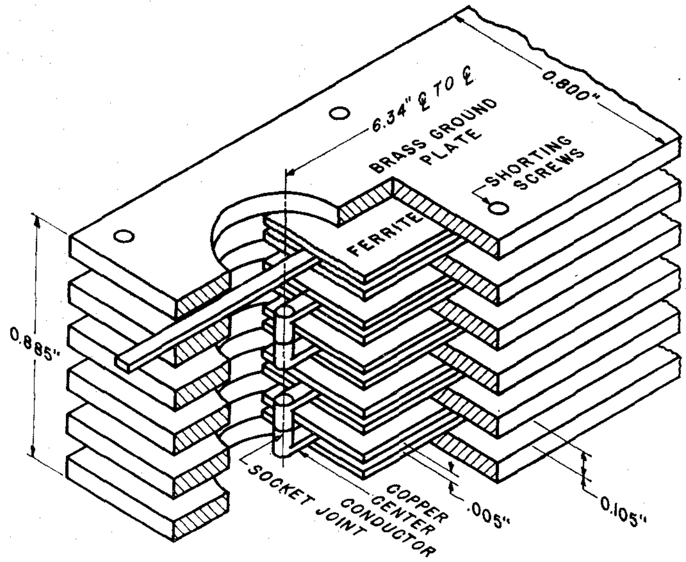


Fig. 1—Cross section of folded stripline phase shifter.

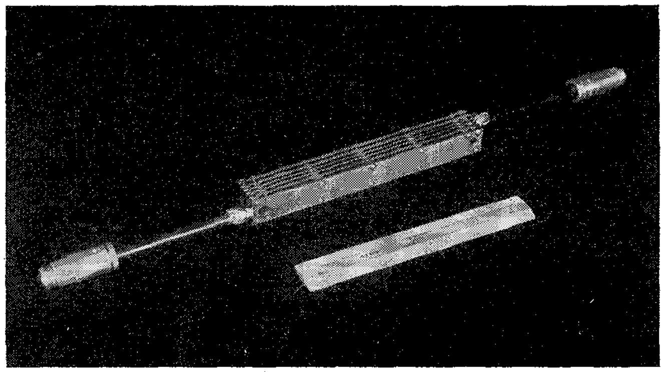


Fig. 2—Photograph of stripline phase shifter.

The phase shifter has generally been operated in a longitudinal magnetic field supplied by a 12-inch long solenoid. The structure fits easily into the $1\frac{1}{4}$-inch inner diameter of the coil, and a reasonably uniform magnetic field is attained (±5 per cent), since the device extends only over the middle half of the solenoid.

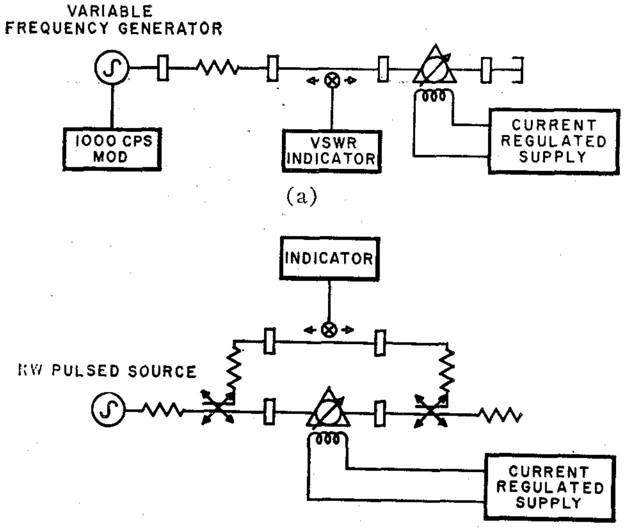
Ferrite Material

Previous to our work, Chu Associates[1] made a series of measurements in the 225 to 400-mc region on $\frac{1}{4}$-inch long samples of ferrite materials shaped to fit a coaxial line. They found that phase shifts of 183° per db of loss could be attained at 400 mc and 169° per db at 225 mc. Their best results were attained with nickel-cobalt-aluminum ferrites.

In the phase shifter described here, type TT-414 ferrite, manufactured by Trans-Tech, Inc., was used. This is a magnesium-manganese-aluminum ferrite with a saturation magnetization of 600 oersteds and a Curie temperature of about 100°C. With this material in the stripline structure, we have measured phase shifts of 400° per db of loss at 400 mc and 300° per db of loss at 225 mc. These measurements, in contrast to Chu's, were made on long samples of the ferrite (6-inch), and the attenuation includes conductor loss.

MEASUREMENTS

Fig. 3 shows schematic diagrams of the measuring systems used to determine the characteristics of the phase shifter. At low-power levels (milliwatts) a simple reflection scheme with one end of the phase shifter shorted was used to measure phase shift as a function of applied field. A phase shift of 180° is indicated by a half wavelength change on the slotted line. Input VSWR was measured with one end of the phase shifter terminated in a 50-ohm load. Insertion loss was measured by first setting a reference level with the phase shifter removed from the circuit and then inserting the device and recording the attenuation for various values of magnetic field.



(a)

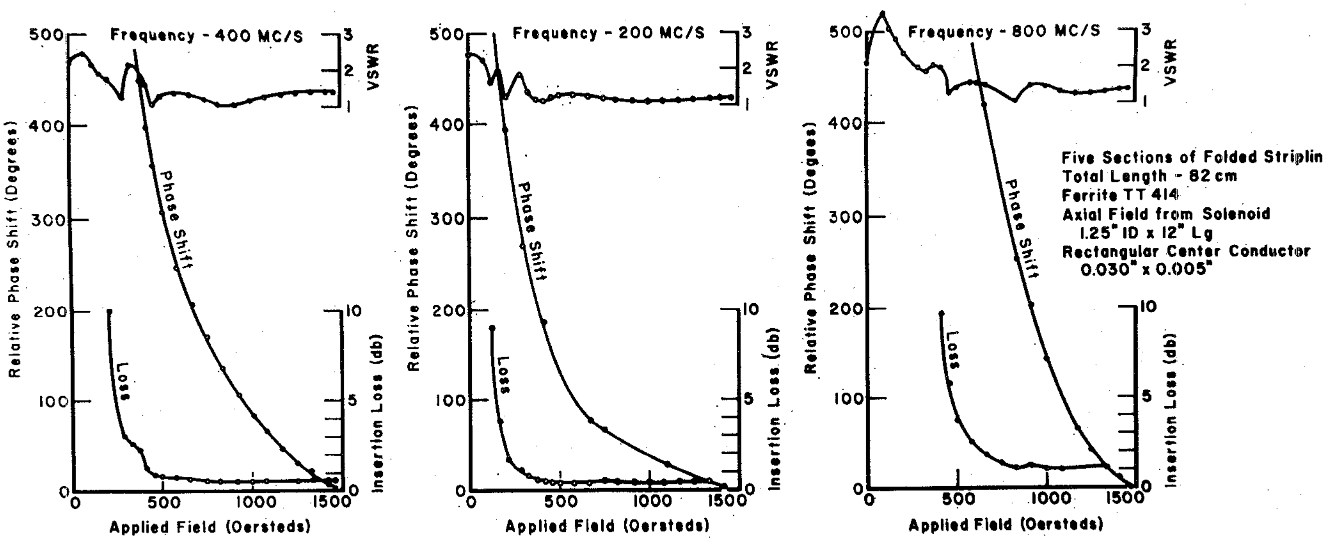
(b)

Fig. 3—(a) Low-power measuring system. (b) High-power measuring system.

At high-power levels (kilowatts) the phase shifter was located in the high-power line and terminated in a 50-ohm load. A directional coupler was inserted in the line on each end of the phase shifter, and the low-level energy coupled from each of these points was sent in opposite directions through the slotted line. In this case, a phase shift of 360° produces a half wavelength change in the probe position. Input VSWR was measured by inserting two identical directional couplers back-to-back at the input to the phase shifter and again sending the coupled signals through the standing wave machine in opposite directions. Insertion loss was measured in the same manner as for the low-power case, except that the crystal detector was isolated from the high-power line by a directional coupler.

---

[1] Chu Associates, "Ferrite Feasibility Study," Interim Dev. Rep. No. 3, Contract No. NObsr-72586; December 1, 1956–March 31, 1957.



(a) (b) (c)

Fig. 4—Phase shifter characteristics at (a) 400 mc, (b) 200 mc, and (c) 800 mc.

RESULTS

Although the range of interest was originally 200 to 600 mc, the characteristics of the phase shifter have been investigated over the frequency range from 2 mc to 2000 mc. The optimum region for the particular length and configuration chosen, however, appears to be 300 to 600 mc.

Typical characteristics of the phase shifter are shown in Fig. 4. At 400 mc, Fig. 4(a) indicates that for an insertion loss of 1 db, 360° change in phase shift (hereafter denoted as relative phase shift) is obtained when the magnetic field is changed from 430 to 1250 oersteds; $\Delta H = 820$ oersteds. The maximum VSWR over this range is 1.45. It can be seen from the graph that the insertion loss has its maximum value of 1 db at the low-field limit of 430 oersteds, and decreases to approximately $\frac{1}{2}$ db by the time the field reaches 700 oersteds. A phase shift of 360° can be obtained for $\frac{3}{4}$-db loss, if the field swing is increased to cover the range from 460 to 1600 oersteds.

Fig. 4(b) shows a similar set of phase shifter characteristics taken at 200 mc. Here 360° phase shift is obtained with a 1.6-db insertion loss when the field is changed from 220 to 1500 oersteds; $\Delta H = 1280$ oersteds. The maximum VSWR in this case is 1.8, again occurring at the low-field end of the range where the ferrite loss is beginning to increase. A better match in this region would result in a sizeable reduction in insertion loss. Even so, for optimum performance at 200 mc, the length of the phase shifter should be increased by about 25 per cent. In this case, the loss would be reduced to 1 db for 360° phase shift, and the required field change would only be from 280 to 1180 oersteds ($\Delta H = 900$ oersteds).

The 800-mc characteristics of the phase shifter are shown in Fig. 4(c). In this case, 360° phase shift is obtained for an insertion loss of 1.4 db and a field change from 730 to 1630; $\Delta H = 900$ oersteds. If the field limits were shifted to higher values, the insertion loss could be reduced to approximately 1 db.

The loss values given in Fig. 4 are actual insertion losses uncorrected for VSWR. If a better match were attained at lower field values, then 360° phase shift with 1-db loss could be attained for an appreciably smaller field change.

From these four sets of data it can be seen that the insertion loss in the low-loss region is increasing with frequency, being less than $\frac{1}{2}$ db at 200 mc and 1 db at 800 mc. The rate of increase appears to be $>\sqrt{\nu}$ but $<\nu$, where ν is the frequency. This indicates that the ferrite losses and the conductor losses are comparable. A calculation of the conductor loss for the stripline, as used here with copper conductors, gives 0.23-db loss at 200 mc and 0.46-db loss at 800 mc, which indeed verifies that the two losses are comparable.

From the data it can also be seen that the low-loss region is moving to higher values of magnetic field as the frequency increases, which, of course, it should, since the resonance region at higher frequencies occurs at larger fields. Eventually, the resonance reaches such a high field value that it is no longer practical to operate on the high side.

As mentioned previously, measurements on the phase shifter were extended over a much wider frequency range than was at first anticipated. Fig. 5 gives a summary of the data obtained from 10 mc to 2000 mc with the folded stripline of 82-cm total length. For convenience, the phase shift curves from 100 mc to 2000 mc are approximately normalized to an origin between 1500 and 1600 oersteds. The lower frequency curves are beginning to approach saturation in this region. The loss curves shown here are corrected for the small reflection loss in order to make them more universally applicable.

At 10 mc these curves show that approximately 90° phase shift can be obtained for a loss of 1 db. The opti-

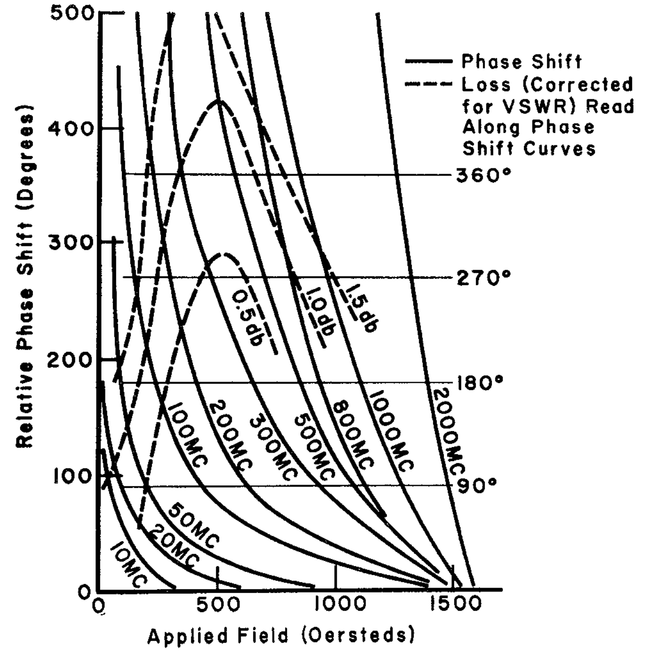


Fig. 5—Summary of phase shift and loss characteristics of folded stripline phase shifter over the region from 10 mc to 2000 mc.

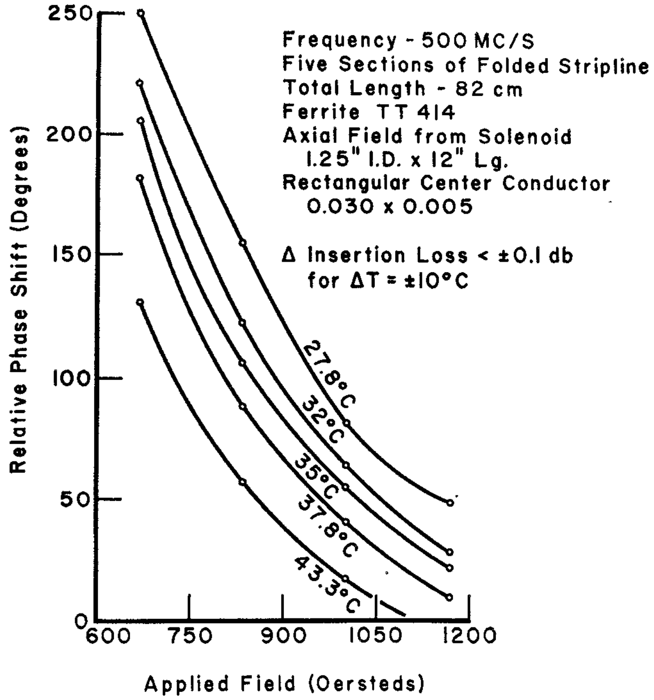


Fig. 6—Temperature characteristics of phase shifter.

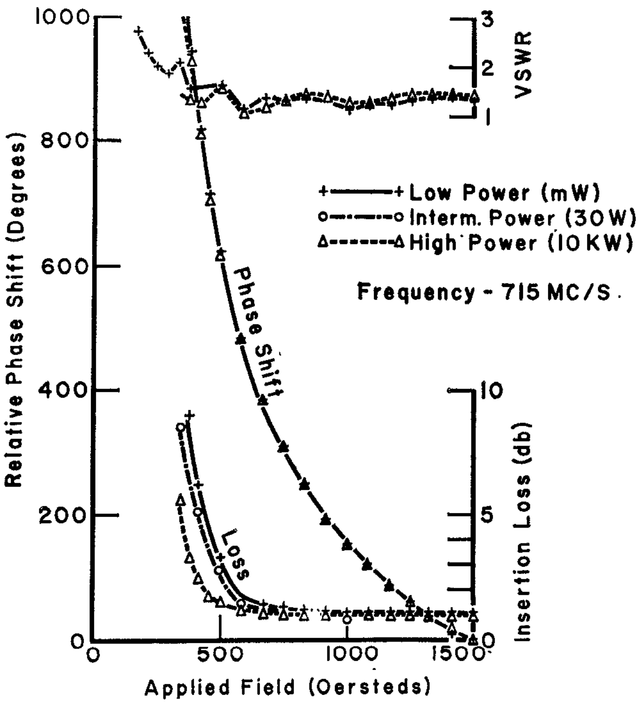


Fig. 7—Comparison of phase shifter characteristics at various power levels.

mum region for this length shifter is indicated quite clearly as the 300 to 600-mc region. At 2000 mc the loss has reached 2 db, but the phase shift function has not approached saturation at our highest field value. At this frequency a much lower loss could be attained by making the device shorter and operating at higher fields.

Temperature effects in the phase shifter were measured by attaching a thermocouple to the ferrite and heating the device by driving the solenoid at high current with the ventilating fan off. Fig. 6 shows the effects obtained at 500 mc. Here the temperature is changed from 27.8°C to 43.3°C ($\Delta T = 15.5°C$) for various field values from 665 to 1165 oersteds. When relative phase is plotted as a function of applied field with temperature as a parameter, the parametric curves are approximately parallel over the region examined. In the low-field region the phase shift change per degree temperature change is greater than in the high-field region. At any particular field value, however, the phase shift change per degree temperature change is approximately linear.

Fig. 7 gives a comparison of the phase shifter characteristics at high, low, and intermediate powers. Three sets of measurements were taken at 715 mc. One set was taken with approximately 10 kw of peak pulsed power. The pulse length was 1 microsecond and the repetition rate was 500 cps. A second set was taken with this same source attenuated 25 db giving a peak output of 30 watts, and a third set was taken with milliwatts of power modulated at 1000 cps. In the low-loss region no measurable difference exists in the phase shift or loss characteristics. As the side of the resonance is approached the loss curves begin to deviate. The loss curve for the lowest power begins to increase at the fastest rate, and that for the highest power at the slowest rate. The phase shift curves begin to show a measurable deviation only at low fields after the loss has reached a high value. These characteristics indicate the onset of a saturation effect.

Besides the foregoing major results, a few miscellaneous observations should also be mentioned.

First, the phase shifts obtained when a transverse magnetic field was applied to the device were considerably less than those obtained with a longitudinal field. The losses were also slightly greater. It should be emphasized, however, that these results are only qualitative, since the field was not uniform.

Second, at 1100 cps the ac modulation current through the solenoid gave about 40 per cent as much phase swing as a dc current equal to the peak-to-peak ac current. Thus, the stripline structure with shorting screws making dc contact with the ground plates shields the ferrite at high modulation frequencies. To overcome this difficulty the shorting screws should be designed to look like RF short circuits but dc open circuits.

Third, resettability of phase shift through the device is limited by the accuracy with which the current can be read (0.1 per cent or better).

Fourth, a few measurements were made using different types of center conductors. A phosphor bronze conductor is more rugged than pure copper and was used at first, but since conductor loss is a major contributor to the total it had to be discarded in favor of the pure copper. A round copper center conductor (0.017 inch) was also tried, but less phase shift was obtained than with the rectangular type. This decrease was attributed to the proportionally greater effect of the air space between the ferrite strips when a round conductor is used.

Fifth, an attempt was made to measure μ_1 and ϵ_1 for the long ferrite samples in the stripline by means of a sliding short technique. The results indicated that $\epsilon_1 \approx 11$ and $\mu_1 \approx 2$, but for accurate results the conductors will have to be plated to the ferrite strips

DISCUSSION AND CONCLUSIONS

The above results show that large differential phase shifts can be obtained with low loss over the entire VHF and UHF bands. In this frequency region the stripline structure as used for the foregoing phase shifter will ordinarily allow only the TEM mode to propagate, *i.e.*, when loaded with the usual nongyromagnetic dielectric. However, it has been shown theoretically that a TEM mode cannot exist in a bounded gyromagnetic medium.[2] The exact mode configuration that does exist in this structure when loaded with a gyromagnetic medium is not clear at present, but the Faraday rotation in the ferrite is certainly restrained. A similar type of restraint of the Faraday rotation has been found by Reggia and Spencer[3] in a rectangular waveguide structure loaded with a long cylinder of ferrite magnetized longitudinally.

The low losses, low VSWR's, and wide range of operation are strong indications that the phase shifter is operating in essentially a TEM mode.

The TT-414 ferrite used in the phase shifter is a magnesium-manganese-aluminum ferrite with a line width at *S*-band of about 120 oersteds. It was suggested by C. L. Hogan that at field values several line widths removed from resonance, polycrystalline magnesium ferrites have been found to have effectively much narrower line widths than the 3-db width indicates. This follows, since the line shape is not Lorentzian; it decays much more rapidly in the wings. Low-loss operation down to a few megacycles at fields of about 50 oersteds indicates a very narrow line width.

Other ferrites have been tried in coaxial structures and were found to have very promising characteristics along with higher Curie temperatures. Extensive tests of these materials in the stripline device have not yet been carried out.

The advantages of operation on the high-field side of resonance is pointed out quite clearly in Fig. 7, where the loss is constant from milliwatt power levels to 10-kw levels. Subsidiary resonances of the type that occur on the low-field side of the main resonance are not present.

In summary, it appears that a ferrite-loaded folded-stripline structure magnetized longitudinally has a range of application as a phase shifter from a few megacycles to a few thousand mega-cycles. The structure is extremely compact and the solenoid size is relatively modest below frequencies of a thousand megacycles. (The actual design of the solenoid will depend on the switching time desired.) The length of the structure should be tailored somewhat to the operating frequency for minimum loss and minimum field swing. Actually, the last two parameters are mutually opposed. The field swings can be reduced considerably if a higher loss is permitted.

ACKNOWLEDGMENT

The author wishes to acknowledge the help of G. Buehler of this laboratory in making the foregoing measurements.

---

[2] P. S. Epstein, "Theory of wave propagation in a gyromagnetic medium," *Rev. Mod. Phys.*, vol. 28, pp. 3–17; January, 1956.

[3] F. Reggia and E. G. Spencer, "A new technique in ferrite phase shifting of beam scanning of microwave antennas," PROC. IRE, vol. 45, pp. 1510–1517; November, 1957.