A Fast Ferrite Switch for Use at 70 KMC*

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***Summary*—A normally open (attenuating) switch using ferrites has been built to operate in the 70-kmc region. It can be operated in 0.5 μsec and can be used with high duty cycles. The attenuation is about one db in the closed position and about 60 db in the open position. Construction and performance of the switch are discussed.**

INTRODUCTION

ONE of the principal difficulties in fast switching of microwaves by means of ferrites lies in getting high-frequency switching field components to the ferrite without interfering with the microwave transmission path. A number of schemes for accomplishing these ends have been proposed and a summary of these methods and some of the attendant difficulties has been given by Uebele.[1] Many of the microwave problems are removed if one can make a hollow waveguide with a metal wall many skin depths in thickness for the microwave frequency and less than a skin depth in thickness at the highest modulating frequency. Such a construction also makes the design of the coil, which provides the switching field, simpler since the coil is not in the microwave field. A copper wall thickness of 0.0001 inch will reduce the amplitude of a 7.5-mc modulating field component by only 10 per cent but it reduces the amplitude of microwave field components by over 99 per cent for 10 kmc and higher frequencies. Waveguides made with 0.0001 to 0.0002-inch walls have been found to be as good as thick wall guides at 70 kmc and at the same time a square current waveform through a coil around such guides allows switching times of 0.5 μsec.

In order to accomplish the switching with modest currents a Faraday rotation device was used. Here the demagnetizing factor can be quite low (about 0.006 in our case) and if a ferrite with small coercive force is used, the driving field needed to change magnetization of the ferrite is small. The 70-kmc switch described here requires only about 6 oersteds of switching field.

RADIO FREQUENCY OPERATING PRINCIPLES

The radio frequency elements of the switch are shown schematically in Fig. 1. Power enters through RG98U waveguide at end 1 and goes through a tapered transition to 0.150-inch round waveguide. The polarization of the electric vector is indicated in the chart also on Fig. 1. The electric polarization is normal to the plane of a resistance film 2 and the wave is not affected if this film is made properly (see Appendix). When the switch is closed (transmitting) the ferrite in 3 rotates the polarization ($90° + \theta$) to 4 on the chart. This polarization is normal to the centrally located lossy film and the wave is not affected by the film and is as indicated in 5. The second ferrite 6 rotates the polarization ($90° + \theta$) in the opposite direction from the earlier rotation. The polarization of the wave is then normal to the lossy film 7 and the wave passes through the round-to-rectangular transition section and out 8 which is again RG98U waveguide. If there is no applied magnetic field the switch will be open (not transmitting), and referring again to Fig. 1 we can trace through the behavior of the switch. Power again enters 1 and is incident on the ferrite loaded section 3 as before. The ferrite will cause a small (at most 5 degrees) rotation of the polarization because of the remanent magnetization of the ferrite. This rotation is indicated by the small angle θ in 4 on the chart of Fig. 1. The lossy film is now parallel to the polarization and absorbs the power from the wave. There are, however, a number of factors which can cause a small amount of power to remain in the ploarization normal to the lossy film. For example, the Faraday rotation is somewhat frequency-sensitive so that θ will depend on frequency. Also, mechanical imperfections can cause the wave polarization to be slightly elliptical. Thus, there will be some power polarized normal to the lossy film and this will be unaffected by the film and will emerge as indicated at 5. The second ferrite loaded section, 6, will rotate this component an amount θ in the opposite sense from the first rotation and the wave will then be polarized as shown in 7. This polarization is in the plane of the lossy film and will be absorbed, so that the double switch section gives higher loss and operates over a wider band.

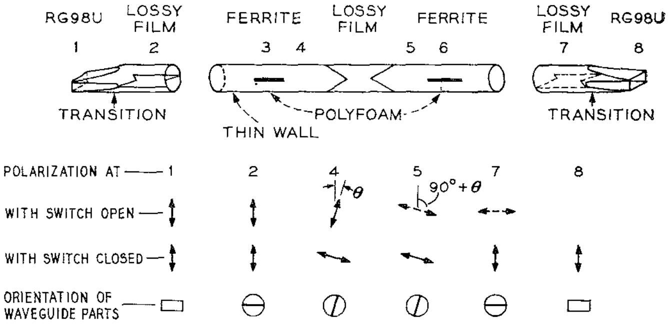

Fig. 1—Schematic of RF switch.

DESIGN OF ROTATION SECTIONS AND SWITCHING COILS

The magnitude of the driving field required to produce 90 degrees of rotation in the Faraday rotation sections depends on the ferrite used, the radio frequency in-

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[1] G. S. Uebele, "High-speed ferrite microwave switch," 1957 IRE NATIONAL CONVENTION RECORD, pt. 1, pp. 227–234.

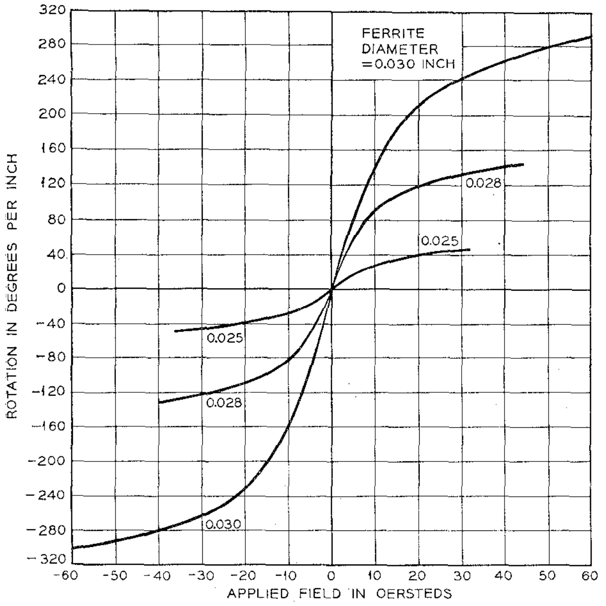

Fig. 2—Rotation of 70-kmc wave in 0.150-inch ID round guide as a function of applied field.

volved, the guide diameter, and the length and diameter of the ferrite. The ferrite chosen is a nickel zinc ferrite [$Ni_{0.6}Zn_{0.4}Fe_{1.9}Mn_{0.02}O_4$] with the highest saturation magnetization (4900 gauss) available in a material with low coercive force. This provides the maximum effect because of the large magnetization and at the same time the switching fields are small because of the low coercive force. In Fig. 2 the rotation of a 70-kmc wave in degrees per inch of ferrite length is shown as a function of applied field for 0.025, 0.028, and 0.030-inch diameter ferrite rods in 0.150-inch ID round waveguide. The field was varied continuously from a given value in one direction through zero to a given value in the opposite direction and the rotation at zero field was arbitrarily chosen as zero degrees. Ferrite diameters larger than 0.030 inch cause erratic behavior in the rotation vs field plots and we attribute this to generation of higher order modes. The 0.030-inch diameter ferrite does not produce excessive loss or reflection and it was generally used for the switch application because it requires the smallest driving field. (The most serious objection to 0.030-inch diameter ferrite is the frequency sensitivity of the rotation. For applications in which there is no difficulty in providing a field of 25 gauss or more the smaller diameter ferrites are desirable because their rotation vs frequency characteristic is much flatter. A one-inch length of 0.025-inch diameter ferrite is used for the Faraday rotation element in isolators built for the 70-kmc region.)

After the various parameters mentioned above are fixed, it is necessary to decide how long the ferrite rod is to be, and hence how much switching field is required. If the ferrite is made too long, its RF loss is unnecessarily large and the fact that small switching fields are required means also that the switch behavior is affected by stray fields in the vicinity. The coils that provide the switching fields are wound on the outside of the thin wall waveguide and have a diameter small enough to allow the field on the axis of the coil to be calculated approximately from the long solenoid formula for all points not too close to the end of the coil. Accordingly, if the coil projects one-eighth of an inch beyond the ferrite rod at either end it is possible to specify roughly the number of ampere turns required to operate the switch for different ferrite lengths and diameters. This assumes that the ferrite does not appreciably affect the fields in the coil. The assumption is justified in the case of a 0.34-inch diameter coil by the small change in inductance observed when the ferrite is inserted. For coils of 0.20-inch diameter the observed inductance change was large since the ferrite occupies a larger fraction of the coil volume. However, the calculations at least give approximate agreement with our experimental results. In Fig. 3 the number of ampere-turns needed to produce 90 degrees of rotation at 70 kmc is plotted against ferrite length for 0.030-inch and 0.028-inch ferrite diameters in 0.150-inch ID round guide. A length of 0.5 inch of 0.030-inch diameter ferrite in 0.150-inch ID round guide appears to be a natural choice since the ampere-turns required for shorter lengths rises rapidly and the number of ampere turns required for longer lengths is not very much less.

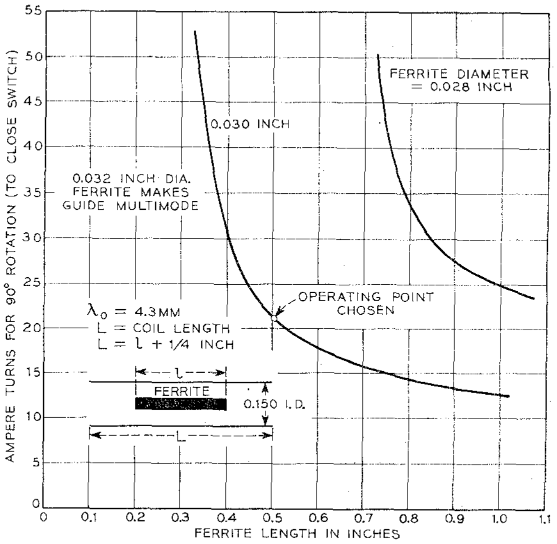

Fig. 3—Ampere-turns needed to close switch.

Behavior of Switches

Some switches have been constructed using the electrical principles outlined above. These switches have been tested in two different ways. First, in order to get a good measurement of the loss in the open and closed positions the switches have been tested with direct current through the coils. The attenuation vs current behavior of one of the switches is shown for frequencies of 69.3 kmc, 69.8 kmc, and 71.7 kmc in Fig. 4. Second, in order to test the high-speed switching characteristics of the switches they have been tested with square wave

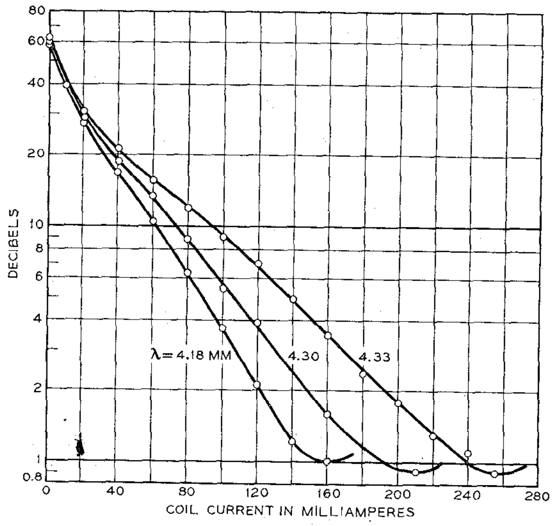

Fig. 4—Attentuation of switch for varying coil current.

modulation. The detected RF modulation envelope and the current waveform through the driving coils are shown in Fig. 5 for 100-kc square wave modulation. The attenuation vs current characteristic, Fig. 4, is such that even a nonsquare current waveform will produce a fairly square RF envelope. The switches have been driven at up to 250 kc and still produce a recognizable square wave. The coils used overheat if modulating frequencies of a megacycle are used, but with different coils the switches can be made to modulate at a 1-mc rate. It has been reported[2] that such high modulation rates cause the ferrites to heat up because of hysteresis losses to the point where polystyrene supports melt. There has been no such difficulty with this switch construction. Presumably, the fact that the ferrite is switched over only a small portion of the hysteresis loop reduces the energy dissipated per unit volume to a tolerable level. This operating condition is possible, of course, because the ferrite sections used are ample to produce 90 degrees rotation with only small driving fields.

Construction of Switch Unit

Good performance of the switch requires a high quality thin wall waveguide. That is, the inside surface must be uniform and polished and the wall thickness must lie in a range which permits the switching field to penetrate, yet guides the RF field as was indicated earlier. The thin wall is made by electroforming copper on a stainless steel mandrel which is made of AISI Type 303 or 316 stainless steel and is ground and polished to a diameter of 0.150 inch over a four-inch length. The mandrel is shown in Fig. 6(a). A copper coating less than 0.0002 inch thick is deposited on the mandrel from a standard acid copper plating bath. The plating on the ends of the mandrel is built up to about 0.030 inch. This thicker wall is necessary to insure good electrical contact at the ends of the guide, since the RF connections to other guides are butt joints. After washing and drying, the work is then cast in an epoxy resin. The casting mold must be either pliable or made of a material (such as Teflon) to which the casting resin will not adhere; otherwise the casting resin will pull the thin copper plating from the mandrel as the plastic contracts during curing. After the plastic is cured the assembly is turned down as indicated in Fig. 6(b). Finally the mandrel is removed by simply pulling it out at room temperature. The ends of the finished waveguide are then faced off. All that remains is to wind the coils [Fig. 6(d)] and load the guide with a lossy sheet and the ferrite pieces [Fig. 6(c)].

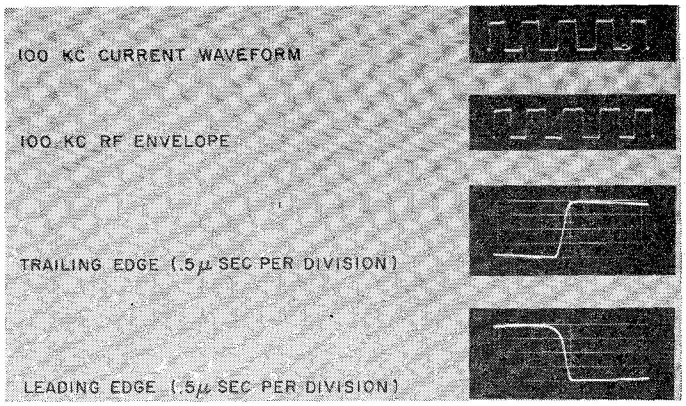

Fig. 5—Response of switch to square current waveform.

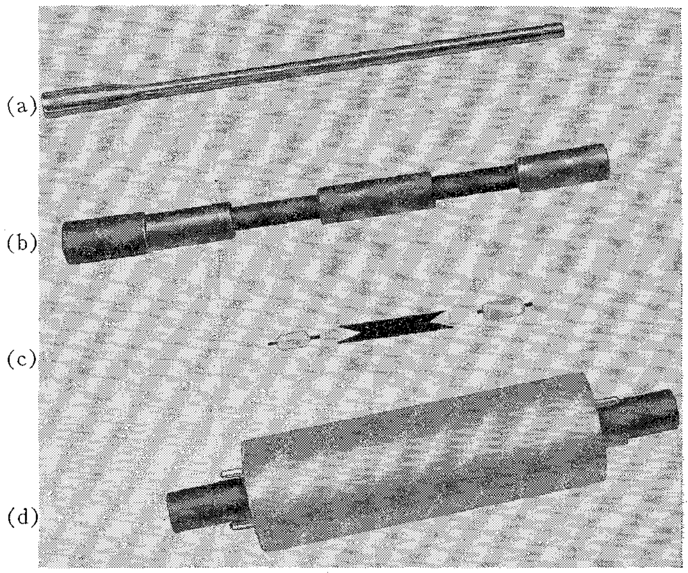

Fig. 6—(a) Stainless steel mandrel. (b) Epoxy resin jacket on thin wall section. (c) Ferrites and central lossy film. (d) Completed switch with coils.

Conclusion

The construction and performance of a normally open ferrite switch operating in the 70-kmc region has been described. Attenuations of about 1 db and 60 db can be obtained in the two switch positions, and the switching time to the 90 per cent points is about 0.5 μsec. The emphasis in the discussion has been placed on this one

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[2] W. N. Honeyman and R. S. Cole, "Hysteresis heating of microwave ferrites," Proc. IRE, vol. 45, pp. 1285–1286; September, 1957.

specific switch type but much of the information could be used in designing a normally closed switch or a three-position switch using a cross polarization pick-off to retrieve the power dissipated in resistance sheets. Many of the design principles discussed apply equally to more general types of amplitude modulators.

APPENDIX

Because of the high frequencies and small sizes involved in the 70-kmc region the ordinary resistance sheet made by evaporating metal film on a dielectric backing sheet causes loss to the wave whose polarization is such that the wave is ordinarily considered to be unaffected. This loss arises in the following fashion. A dielectric sheet stretched across dominant mode waveguide so that its plane is everywhere perpendicular to the plane of the dominant mode electric vector of the empty guide causes components of electric field to occur parallel to the sheet in the altered dominant mode configuration. These field components along the dielectric will cause current flow and hence loss if one or both sides of the dielectric are coated with a metal film. If the sheet is centered on a diametral plane of a round cylindrical waveguide the tangential field components vanish on the diametral plane itself so this is clearly the place to put the evaporated metal film. Accordingly, the resistance sheets used in the switch are made by evaporating metal on one dielectric sheet and covering this with a second dielectric sheet of equal thickness.

The propagation constant of a rectangular waveguide containing a dielectric sheet coated with a film of conductivity σ ohms^{-1} on each side has been obtained by solving the appropriate boundary value problem and this solution indicates the magnitude of the loss expected in the actual circular waveguide. The rectangular guide has a height b, the dielectric thickness is c, and the dielectric center plane lies on the center plane $(b/2)$ of the guide. If the attenuation constant α is small compared to the free space phase constant β_0, and if c is small compared to b, the attenuation constant and phase constant β can be expressed simply:

$$\alpha = 377 \frac{c^2}{2b} \beta_0{}^2 \sigma \left(\frac{\epsilon_r - 1}{\epsilon_r} \right)^2,$$

$$\beta = \beta_0 \left[1 - \frac{\pi^2}{a^2 \beta_0{}^2} + \frac{c}{b} \left(\frac{\epsilon_r - 1}{\epsilon_r} \right) \right],$$

where ϵ_r is the relative dielectric constant of the dielectric sheet and a is the width of the waveguide. The attenuation per wavelength becomes appreciable at very high frequencies only because c, the dielectric thickness, cannot be scaled down indefinitely. Experimentally, we have found that a coating of 0.01 ohm^{-1} on a 0.0035-inch piece of Nylar ($\epsilon_r = 3.7$) in 0.150-inch round guide causes a loss of 0.75 db per inch at 70 kmc. The theoretical prediction from the above equation is 0.625 db per inch in 0.148-inch square waveguide. If the conducting film is centered in the dielectric sheet, as mentioned earlier, symmetry requires that there be no conduction loss since the electric field is everywhere normal to the film and the film is much less than a skin depth in thickness. Experimentally, a film constructed in this fashion produces less than 0.1 db per inch of loss in the orthogonally polarized wave.

Theoretical Analysis of the Operation of the Field-Displacement Ferrite Isolator*

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Summary—**A theoretical analysis of the resistance-sheet isolator is carried out, and numerical solutions are obtained for the forward and reverse propagation constants of the distorted dominant mode in a rectangular waveguide containing a transversely magnetized thick ferrite slab displaced slightly from the side wall. The microwave electric field patterns within the waveguide are plotted for several values of the physical design parameters of the isolator for which experimental performance data have been reported. Field patterns are used to describe the principles of the isolator and to select the optimum values of slab thickness, internal dc magnetic field, ferrite magnetization, and location of the slab in the waveguide for the idealized isolator. Evidence is presented to show that it is necessary to use a comparatively thick ferrite slab located in a very small usable range of distances from the side wall. The appropriate value of internal dc magnetic field is simply related to the magnetization of the ferrite and to the frequency. It has not been necessary to take into account the perturbing effects of the resistance card or matching techniques in order to explain the basic design principles.**

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