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A Study of the Soohoo-Type Ferrite Cutoff Switch

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ABSTRACT

The characteristics of the Soohoo-type cutoff switch have been measured at X band. Two types of switch configuration were employed; in one, a single ferrite slab was placed against a waveguide sidewall, and in the other two ferrite slabs were placed against opposite sidewalls. The switch is made to operate between an "on state" (or propagation state) and an "off state" (or reflection state) by application of a transverse magnetic field to the ferrite. This action reduces the effective waveguide width and causes cutoff.

Low-power-level switching characteristics were studied as a function of switch geometry, and a group of switches meeting minimal specifications were selected for study at high-power level. The effect of varying waveguide width, the variety of ferrite used, and the width of the ferrite slab on nonlinear loss were studied at high-peak-power level as a function of applied magnetic field. Some techniques which tended to reduce nonlinear loss were noted.

PROBLEM STATUS

This is an interim report; work continues on other phases of the problem.

AUTHORIZATION

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A STUDY OF THE SOOHOO-TYPE FERRITE CUTOFF SWITCH

INTRODUCTION

In July 1959, R.F. Soohoo (1a) published an article which describes a reflection type of ferrite cutoff switch. The theory and operating characteristics are presented in his article, together with supporting experimental data taken at low rf power levels.

One important application suggested by Soohoo (1a) involves a pair of switches combined in a tee or wye configuration by means of which power can be switched between two loads. For proper operation it is required that in the cutoff condition the switch be as nearly a pure reactance as possible. Since the resistive loss of the ferrite may increase with power level, it is possible that at high power levels the switch might deviate considerably from the purely reactive state. To resolve this question, as well as to obtain other design information, a study was undertaken of the switching characteristics as a function of various parameters determining the ferrite-waveguide configuration. Three readily available ferrite materials were used in the study. One material was chosen because it was known to have a very low threshold for nonlinear loss. In this way the effect of varying the ferrite-waveguide configuration on nonlinear loss could be observed at relatively low power levels. No attempt was made to find the "best" ferrite material for use at any given power level. However, it was hoped that the results of this study would apply generally to any good ferrite material which might be selected for use. Thus, the purpose of this study was to investigate the effects of various design parameters on the operation of this type of switch at both high and low rf power levels. This investigation was not concerned with producing an optimum switch design for any given power level, but rather with discovering general trends useful for optimizing switch operation with respect to the design parameters involved.

Two different Soohoo switch configurations were studied; in one a single ferrite slab of thickness δ was placed against a waveguide sidewall, and in the other two ferrite slabs of thickness $\delta/2$ were placed against opposite sidewalls (Fig. 1). The ferrite is magnetized by an applied field transverse to the broad dimension of the waveguide.

The Soohoo switch is an on-off switch characterized by low insertion loss and high reflected-signal loss in the "on state" and high insertion loss and low reflected-signal loss in the "off state." The operating principles can be understood by recalling that two kinds of solutions to the wave equation are possible for waveguide. One solution corresponds to propagating waves, and the other to damped, or attenuated, waves. Transition from one kind of solution to the other occurs when the propagation constant β changes from a real number to a pure imaginary number (at this point $\beta = 0$). This transition, referred to as the "cutoff point," is characterized by a cutoff wavelength (or frequency) which depends on the effective waveguide width.* When a waveguide is loaded by an unmagnetized ferrite slab, a cutoff frequency f_c exists for the lowest mode. The cutoff frequency will depend on the waveguide width L, the ferrite slab thickness δ, the relative dielectric constant ϵ, and the equivalent relative permeability μ_e of the ferrite slab. If, when the ferrite is unmagnetized, and for fixed L and δ, an operating frequency $f_o > f_c$

*The term "effective waveguide width" refers to the empty waveguide width which would produce the same guide wavelength. The term "cutoff value of waveguide width L_c" will refer to the widest empty waveguide which would be cut off at a given frequency. The cutoff value is determined by the condition $L_c = \lambda_c/2$. For an operating frequency of 9.375 kMc, $L_c = 0.630$ in.

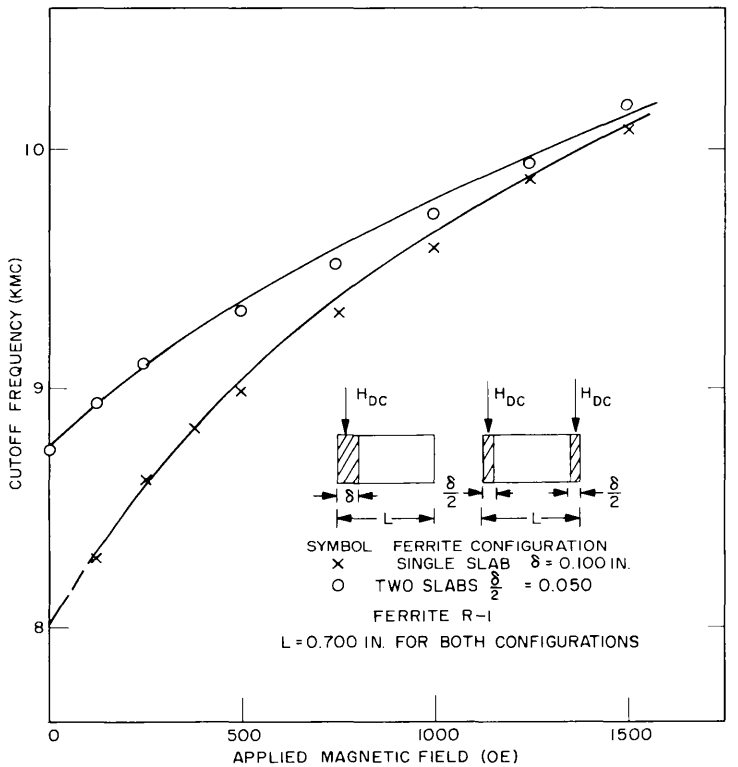

Fig. 1 - Cutoff frequency as a function of applied field for switches composed of a single δ = 0.100 in. slab and two $\delta/2$ = 0.050 in. slabs in L = 0.700 in. waveguide

is chosen, the switch will be above cutoff and a propagation solution to the wave equation will exist. As a magnetic field is applied, the effective permeability of the ferrite is reduced. This in turn decreases the effective waveguide width and increases the cutoff frequency. When the cutoff frequency becomes greater than the operating frequency, the switch will be below cutoff, and only damped-wave solutions to the wave equation will exist. In the cutoff condition, strong reflection from the ferrite-loaded section will occur, and the rf electric field will decrease exponentially as it penetrates into the ferrite region. Thus, the "on state" (or propagation state) of the switch is defined by a region of applied magnetic-field values over which the operating frequency of the switch is greater than the cutoff frequency. Similarly, the "off state" (or reflection state) is defined by a region of applied magnetic-field values over which the operating frequency is less than the cutoff frequency.

Figure 1 shows experimentally determined values of cutoff frequency as a function of applied magnetic field for two R-1 ferrite switches. Consider the curve for the switch consisting of a δ = 0.100-in. slab in a 0.700-in.-width waveguide. If an operating frequency f_o greater than 8.0 kMc is chosen, then the unmagnetized switch will be above cutoff. As an example, let us choose f_o = 9.0 kMc. As the applied magnetic field is increased, the cutoff frequency f_c will be increased until the condition $f_c > f_o$ is satisfied for applied field values greater than 500 oersteds. Thus, when an operating frequency of 9.0 kMc is chosen, this switch is "on" for field values less than 500 oersteds, and "off" for field values greater than 500 oersteds.

This study consisted of two investigations. First, an investigation was conducted at milliwatt power level to observe the general effect of the various design parameters on

switch transmission and reflection characteristics and to select a relatively uniform class of switches for further study at high power level. In the second investigation, the nonlinear loss characteristics of the selected switches were measured at high power levels. Since many applications for which this kind of switch is uniquely qualified utilize the off-state reflected signal as well as the on-state transmitted signal, techniques which tend to reduce losses in both signals were sought.

INVESTIGATION AT MILLIWATT POWER LEVEL

Preliminary Considerations

Prior to beginning the primary study at milliwatt power level, some preliminary consideration was given to the scope of the study and to how a practical basis for comparison of data could be provided. For example, it was decided that the study would be conducted at a fixed frequency and that waveguide width and slab thickness would be variable parameters, while slab length would be held fixed. Also, a practical definition of "on state" and "off state" was established.

The fixed frequency of 9.375 kMc was chosen. This is the frequency of an available high-power magnetron, and if the high-power-level study is to be meaningful, the switches should have good low-power characteristics at this frequency.

Three parameters to be used in comparing the switching characteristics were established. The parameter "on-state loss" will describe the on state and is defined as the value of switch insertion loss which occurs at zero applied field. This single point was chosen because while the on-state region is defined for all values of applied field for which the switch is above cutoff ($f_o > f_c$), the zero-field point is always included. The parameter "off-state loss" will describe the off state and is defined as those values of switch reflected signal loss which occur when the insertion loss is at least 30 db. The value of applied magnetic field required to produce 30 db insertion loss will be referred to as the off-state field. In evaluating the low-power switching characteristics, the minimum value of off-state loss will be used. This value assures that the signal transmitted through the switch is very small, while the reflected signal is as large as possible. It should be noted that minimum off-state loss does not necessarily represent the minimum reflected-signal loss (maximum-strength reflected signal), since this minimum value might occur before 30-db insertion loss is obtained.

An empirical method was used to determine the ferrite slab length to be used in the sample switches. As a starting point, a switch similar to the one described by Soohoo (1a) was chosen. The switch consisted of a $\delta = 0.100$ in. R-1 ferrite slab in a $L = 0.700$ in. waveguide. Five slabs having lengths in the range 1.0 to 3.25 in. were used. On-state loss and off-state loss were measured for the various slabs (Fig. 2). Referring to these data, we see that the on-state loss decreases steadily as the slab length is reduced, while off-state loss has a minimum near 2.5 in. This point indicates the optimum slab length. Notice also that the required off-state field increases as the slab is made shorter.

The observed decrease in on-state loss as the slab length is reduced is expected, and is due to the fact that if a signal has a shorter path to traverse, it is attenuated less.

Both the increase in the off-state loss and the accompanying increase in off-state field for slabs shorter than 2.5 in. are related and may be explained in the following manner. In order to achieve a given loss in a transmitted signal as the transmission length is decreased, the attenuation per length must be increased. In waveguide below cutoff, this loss can be attained by further decreasing the waveguide width. In the case of the Soohoo switch, the waveguide is made effectively more narrow by increasing the ferrite magnetization. At first, the desired effect of both producing the required 30-db

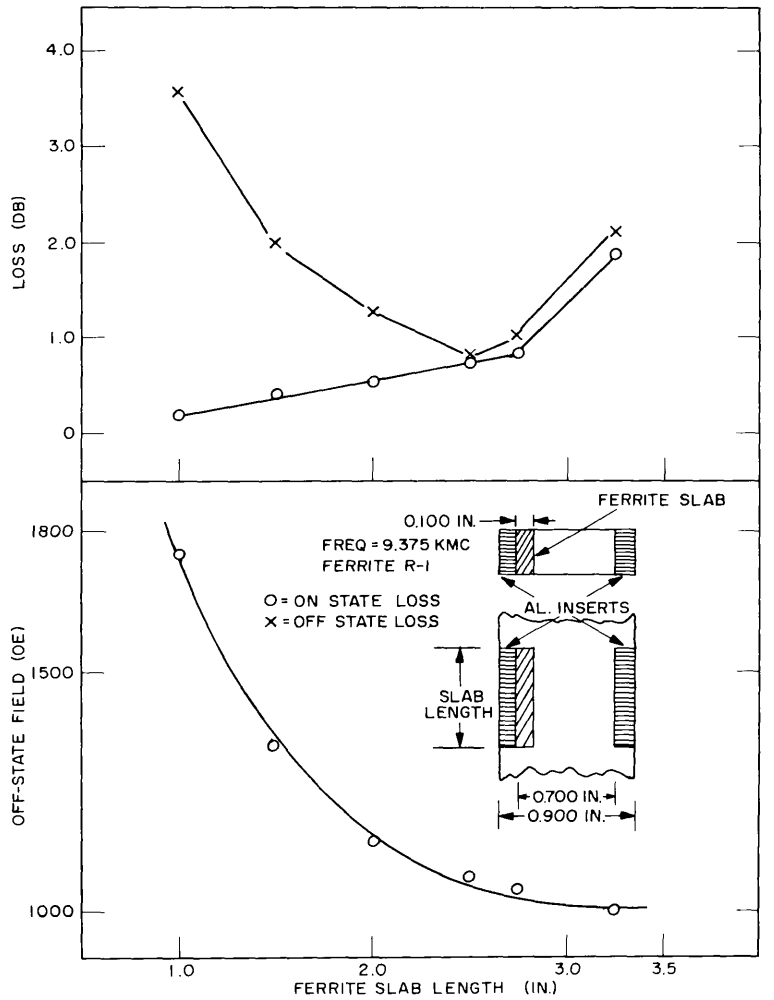

Fig. 2 - Determination of optimum ferrite slab length. On-state loss, off-state loss, and off-state field are plotted as a function of ferrite slab length.

insertion loss and reducing the corresponding off-state loss is achieved. However, continued decreases in slab length and increases in ferrite magnetization will cause the ferrite to approach the value of magnetization required for resonance absorption, and will result in increased off-state loss. Thus we see that the optimum ferrite slab length is determined by the condition that the off-state field be "well below" the field required for resonance. Since the required off-state field will depend on waveguide width L and slab thickness δ as well as slab length, we should expect that the optimum length will also depend on L and δ. When slabs thinner than 0.100 in. are employed, the optimum slab length should be longer than 2.5 in. Thus a standard slab length of 2.75 in. was chosen.

Description of Experiment

The sample switches used in this investigation were obtained by fastening tapered aluminum inserts inside a sample section having the same inside dimensions as RG 52/U waveguide. Switches having widths whose values lie in the range 0.725 to 0.625 in. can be obtained. Ferrite slabs 2.75 in. in length by 0.400 in. in height and of various

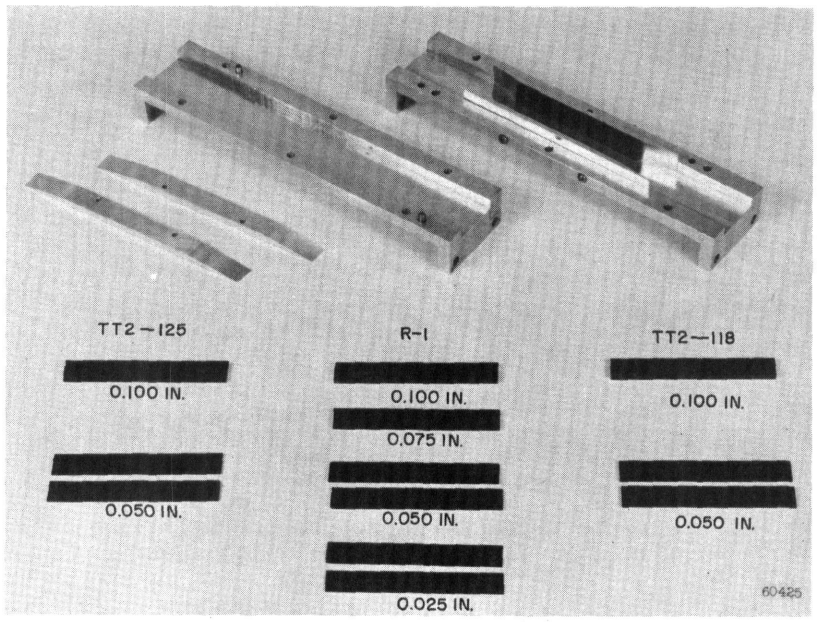

Fig. 3 - X-Band Soohoo switch sample section, showing aluminum inserts and ferrite slabs

thicknesses were cut from three varieties of commercial ferrite. Indiana General Feramic R-1, a magnesium ferrite useful in low-power applications, was used to establish general trends at both low and high power levels. Slabs of R-1 having thicknesses of 0.100, 0.075, 0.050, and 0.025 in. were used. Trans-Tech 2-118, a high-power-level ferrite, and Trans-Tech 2-125 (nickel ferrites) were used to determine the effect of using different kinds of ferrite on switch operation at both high and low power levels. Ferrite slabs TT 2-118 and TT 2-125, having thickness of 0.100 and 0.050 in., were used. The sample section and ferrite slabs are shown in Fig. 3.

In the experimental procedure at milliwatt power, both the insertion loss and the reflected-signal loss of the sample switches were measured as the applied magnetic field was increased from zero to 2500 oersteds, a value of field slightly greater than that required for resonance absorption. A typical microwave reflectometer was used. Measurements were made at a fixed frequency of 9.375 kMc. Other than the use of tapered aluminum inserts, no attempt was made to match the sample switches.

Examination of Data

Typical data are shown in Fig. 4. Data points corresponding to on-state loss, off-state loss, and off-state field are indicated. Data of this type were recorded for all of the available sample switches. Since there are a larger number of R-1 sample switches, the general switching characteristics will be discussed in terms of the R-1 data.

Some general characteristics of the data can be noted. The increase in reflected-signal loss which occurs when the applied field is increased above 1300 oe is caused by the ferrite magnetization approaching the value required for resonance absorption. This phenomenon is described by Soohoo (1a,2). In general, the off-state-field value (and therefore the extent of the on-state region) was observed to depend on switch geometry. Switches closer to cutoff in the unmagnetized state (i.e., more narrow waveguides) have lower values of off-state field.

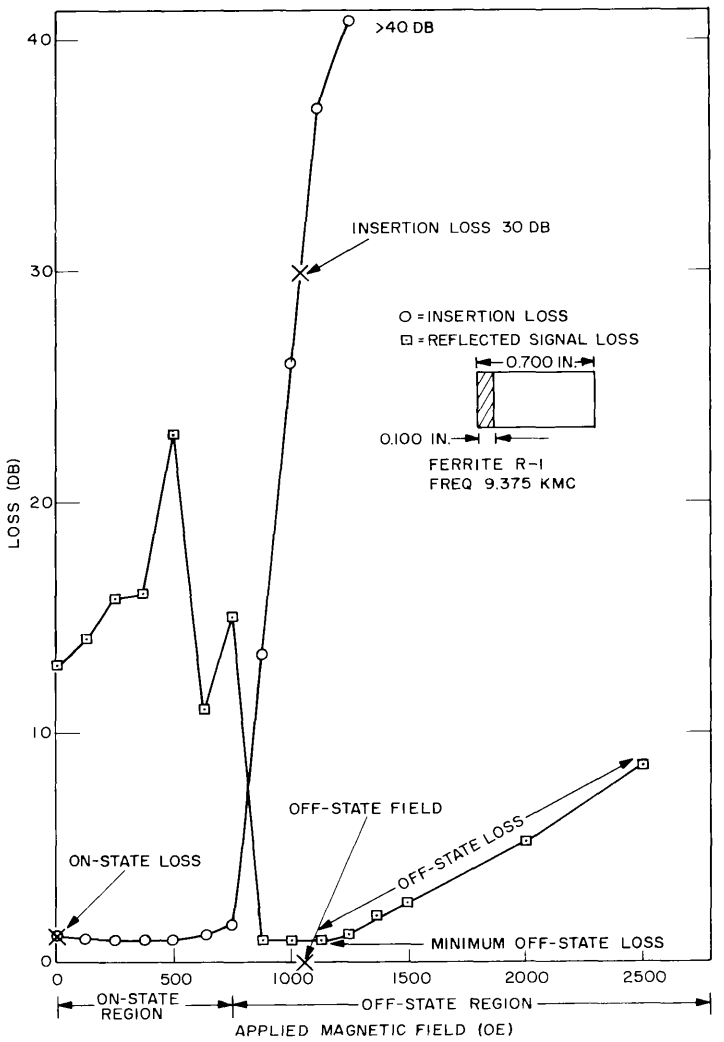

Fig. 4 - Typical dependence of insertion loss and reflected signal loss on applied magnetic field. Data shown are for a switch utilizing a single δ = 0.100 in. R-1 ferrite slab.

The characteristics of a sample switch are described by giving the parameters on-state loss, minimum off-state loss, and off-state field. Figure 5 shows the dependence of these switching parameters on waveguide width and ferrite slab thickness for the R-1 sample switches. In examining these data, consider two ranges of waveguide widths: $0.725 \geq L \geq 0.630$ in. and $0.630 > L \geq 0.625$ in. These ranges represent waveguide whose widths are respectively greater and less than the cutoff value of waveguide width (L_c).*

In examining the data (Fig. 5) corresponding to the first range of waveguide widths ($L > L_c = 0.630$ in.), the following trends can be noted. First, the on-state-loss values increase slowly as either the waveguide width L is reduced or the ferrite slab thickness δ is increased. Second, both minimum off-state loss and off-state field are reduced as the waveguide width L is decreased or as the ferrite slab thickness δ is increased.

*See note on p. 1.

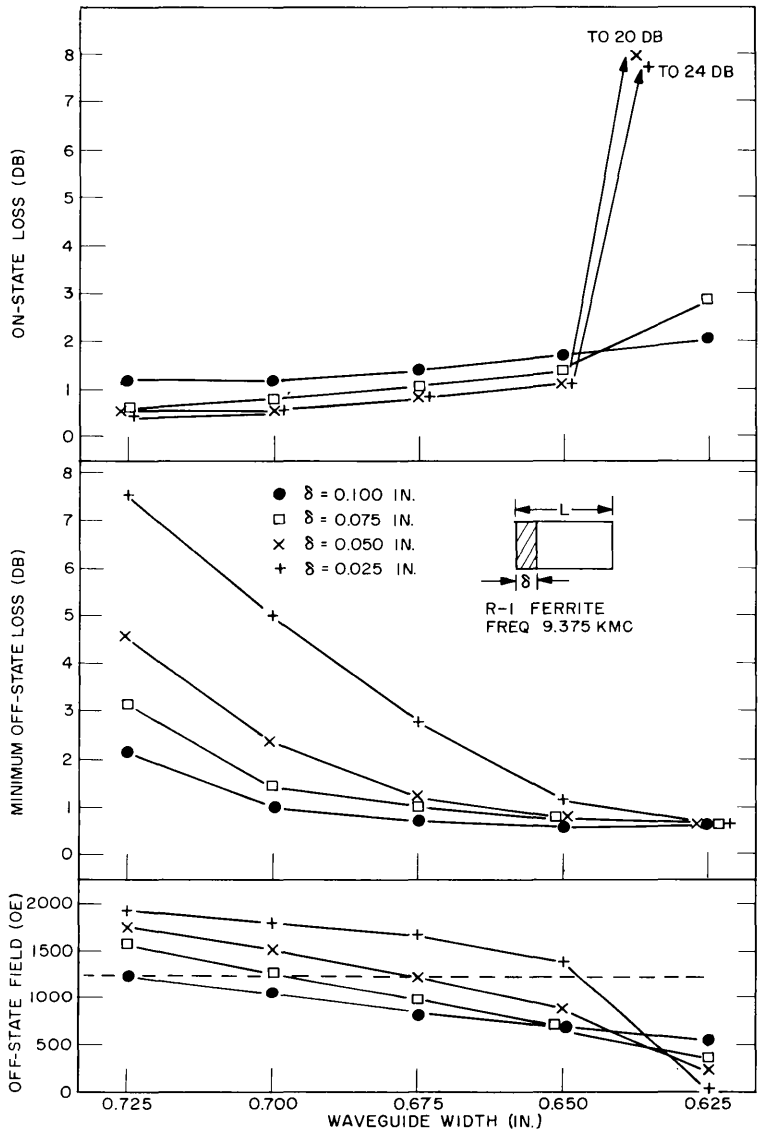

Fig. 5 - Switching parameters of R-1 sample switches. On-state loss, off-state loss, and off-state field are shown as functions of waveguide width, with slab thickness as a parameter.

These trends may be explained in the following manner. The unloaded waveguides are sufficiently above cutoff that the addition of unmagnetized ferrite slabs does not significantly change the effective waveguide width. Their insertion does, however, cause reflection and absorption losses in the transmitted signal, and it would be expected that these losses would be greater for thicker slabs and more narrow waveguides. This result accounts for the observed increase in on-state loss. The observed reductions in minimum off-state loss and off-state field are related, as is seen in the following. The primary function of the magnetized ferrite slab is to reduce the effective waveguide width below the cutoff value L_c. The maximum reduction cannot exceed the thickness of the ferrite slab, so the wider waveguides cannot be cut off when they are loaded by thin slabs. At 9.375 kMc, cutoff

requires $L - \delta < 0.630$ in. When this condition is not met, the observed 30-db insertion loss (which defines off-state field and off-state loss) must be achieved by driving the ferrite magnetization into the main resonance region. This action results in the higher values of both off-state field and off-state loss observed for thinner slabs. When a switch is made physically more narrow by reducing the waveguide width L, the value of off-state field needed to achieve cutoff is correspondingly reduced. This results in lower resonance absorption and therefore lower values of off-state loss.

The data corresponding to the second range of waveguide widths ($L < L_c = 0.630$ in.) shows the following trends. First, the switches having the thicker slabs now require the larger values of off-state field. Second, the two thicker slabbed switches have relatively small values of on-state loss, while the other two switches have experienced a sharp increase in on-state loss. Finally, minimum off-state loss has a small value which is relatively independent of slab thickness. These trends may be explained in the following manner. Over this range of waveguide widths ($L < L_c = 0.630$ in.) the empty waveguide is below cutoff. The insertion of unmagnetized ferrite slabs provides dielectric loading which is proportional to slab thickness. Switches loaded by thicker slabs are farther above cutoff, while those loaded by thinner slabs may still be below cutoff. Thus the thicker slabbed switches have larger values of off-state field, and off-state field decreases when slab thickness is reduced. The two switches having the thinnest slabs are near or below cutoff under zero field, which causes the observed high values of on-state loss and near-zero values of off-state field. Finally, the uniformly low values of off-state loss result from the fact that all the switches achieve cutoff at field values well below the resonance absorption region.

Frequency Bandwidth

The maximum frequency band over which a switch of this type can be operated depends on waveguide width, ferrite thickness, and the physical properties of the ferrite employed. In the following paragraphs the upper and lower frequency limits of the bandwidth will be defined, and the manner in which they are affected by some of these design parameters will be discussed.

The lower-frequency limit is determined by the restriction that the switch be operated above the cutoff frequency * in the on state and will be defined as the cutoff frequency corresponding to zero applied magnetic field.

The upper-frequency limit is determined by the restrictions that the switch be operated below the cutoff frequency in the off state and that the corresponding off-state loss be as small as possible. It was seen in Fig. 1 that cutoff frequency increases with applied magnetic field, causing the upper-frequency limit to be increased, as Soohoo has noted (1b). As the applied magnetic field is increased above 1250 oe, it begins to approach the field value required for resonance absorption. This is characterized by an increase in reflected-signal loss (Fig. 4). Imposing the condition that the off-state loss be maintained near its minimum value requires the use of an applied magnetic field no greater than approximately 1300 oe. The upper-frequency limit can now be defined as the cutoff frequency corresponding to an applied magnetic field of 1300 oe.

Using the above definitions, and referring to the data shown in Fig. 1 for a switch having a waveguide width of 0.700 in. and an R-1 ferrite slab 0.100 in. thick, the upper and lower frequency limits are found to be 9.90 kMc and 8.00 kMc. The maximum bandwidth then is 1.90 kMc, with a center frequency of 8.95 kMc. The term "maximum bandwidth

*Here the mathematically defined cutoff frequency is referred to. Experimentally it is determined by the frequency at which a rapid increase in insertion loss and a rapid decrease in reflected signal loss is observed as the operating frequency is reduced.

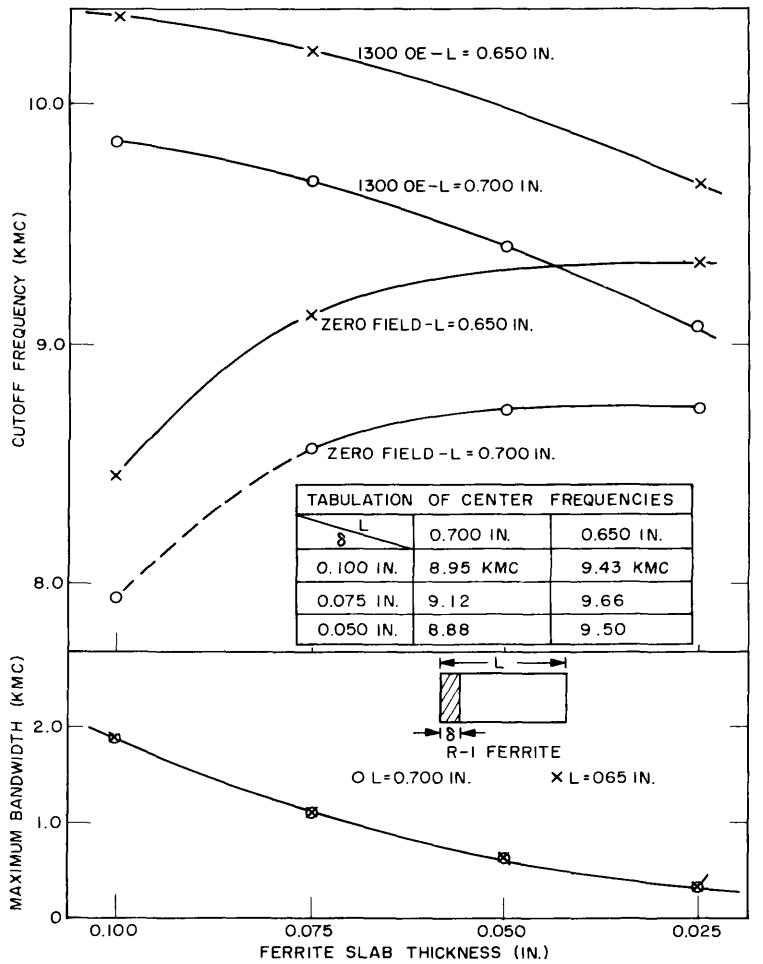

Fig. 6 - Typical operating-frequency characteristics of R-1 sample switches. Upper and lower limit cutoff frequencies and frequency bandwidth are shown as a function of slab thickness for two values of waveguide width.

is used to denote the frequency limits within which the switch must operate. It should be noted that only the upper and lower frequency limits have been determined here; satisfactory operation over the entire band was not observed.

Figure 6 shows experimentally determined values of cutoff frequency as a function of ferrite slab thickness for waveguides having widths L = 0.700 in. and L = 0.650 in. Upper and lower limit cutoff frequencies (corresponding to 1300 and zero oe) are shown. An examination of the data shows that the lower-limit cutoff frequencies (for fixed L) increase with decreasing slab thickness. This result demonstrates the effect of dielectric loading of the waveguide by the unmagnetized ferrite slabs. The thinner slabs provide less loading, which causes the waveguide to be effectively more narrow and increases the cutoff frequency. Also, the change in cutoff frequency which occurs when a given magnetic field is applied is less for thinner slabs. This effect causes the maximum bandwidth to decrease with decreasing slab thickness. Reduction of the waveguide width from 0.700 to 0.650 in. simply shifts the data for both upper and lower frequency limits to higher frequences. The shift in frequency limits results in the maximum bandwidths corresponding to

L = 0.700 in. and L = 0.650 in. switches being very nearly identical in magnitude and causes the center frequencies of the L = 0.650 in. switches to occur at higher frequencies than the L = 0.700 in. switches.

INVESTIGATION AT HIGH-POWER LEVEL

Preliminary Considerations

Below a critical threshold power level, the loss exhibited by a ferrite component is independent of power level. When the threshold level is exceeded, the loss increases with power level. This is the so-called nonlinear effect. The increase in transmitted or reflected signal loss over the loss observed at low power level (below threshold) is termed nonlinear loss.

A Soohoo-type switch exhibits nonlinear loss in both the on-state transmitted signal and the off-state reflected signal. Nonlinear loss in the on-state transmitted signal is readily determined by measuring the variation of zero-field insertion loss (i.e., on-state loss) with peak power level. Determination of nonlinear loss in the off-state reflected signal is complicated by two factors. First, both off-state field and the region of applied field values over which off-state loss is defined depend on switch geometry. Second, the reflected-signal nonlinear loss can depend on applied magnetic field as well as incident peak-power level. For example, a study of the power absorbed by cylindrical ferrite rods in round waveguide (3) showed the classical subsidiary and main resonance regions. One item of particular interest shown in this report is the existence of a value of applied field (between the subsidiary and main resonance) for which the loss is substantially independent of power level. Because of these factors, a meaningful determination of the off-state nonlinear characteristics can be made only by observing the reflected-signal loss as a function of incident peak-power level over a range of applied field values greater than the off-state-field value.

Description of Experiment

The purpose of the experiment at high power level was to determine the effect of switch geometry on both on-state and off-state nonlinear loss. The dependence of nonlinear loss on waveguide width and ferrite slab thickness was determined, and a comparison of the nonlinear characteristics of single and double slab switch configurations was made. The range of switch parameters was limited to those corresponding to the switches shown in Table 1. These switches were selected from those studied at low power level. The selection criterion requires that both on-state loss and minimum off-state loss be at less than 3.0 db. While this requirement is not very rigid and could not be used to define a very practical switch, it does allow the inclusion of a large enough group of switches to observe the general trends. These trends will be discussed in terms of the R-1 sample switches.

An apparatus which provided a photographic record of both insertion loss and reflected-signal loss as a function of peak power level and which minimized rf heating of the sample switches was used. A test modulator and a magnetron were used to generate pulsed rf energy (operating frequency 9.375 kMc, pulse width 1 μsec, repetition rate 1000 pps) of 100 kilowatts peak power. A power meter and a filtered amplifier were used to produce a calibrated dc signal proportional to the incident peak power level. This signal and the dc output of a ratio meter were displayed on an oscilloscope, giving a plot of insertion loss or reflected-signal loss as a function of peak power level. A circulator was used to separate the off-state reflected signal from the incident signal. The nonlinear characteristics of the circulator were determined. There was no error due to this source up to 30 kw peak power, and only 0.4 db error up to 100 kw peak power. These errors

Table 1
Sample Switches Selected for Study at High-Power Level

Ferrite	Configuration	Length L (in.)				
		0.725	0.700	0.675	0.650	0.625
R-1	δ = 0.100 in.	X	X	X	X	X
	δ = 0.075 in.	X	X	X	X	X
	δ = 0.050 in.		X	X	X	
	δ = 0.025 in.			X	X	
	Two slabs $\delta/2$ = 0.050 in.	X	X	X	X	
	Two slabs $\delta/2$ = 0.025 in.		X	X	X	
TT2-125	δ = 0.100 in.	X	X	X	X	X
	δ = 0.050 in.		X	X		
	Two slabs $\delta/2$ = 0.050 in.	X	X	X		
TT2-118	δ = 0.100 in.					
	δ = 0.050 in.			X		
	Two slabs δ = 0.650 in.		X			

X indicates a switch selected for study at high power.

were taken into account when calibrating the equipment and evaluating the data. Thermal losses due to rf heating were isolated (as much as possible) from the nonlinear losses by minimizing the total rf power incident upon the ferrite slabs. This isolation was achieved by rapidly varying the incident power level from zero to maximum peak power and back again to zero, using a motor-driven power divider and by setting the maximum power level at various values with a second adjustable power divider.

Examination of Typical Data

In the high-power-level investigation, the basic quantities measured as a function of peak power level were on-state loss and off-state loss. On-state loss was measured at zero applied field, while off-state loss was measured over a range of field values which extended from the off-state-field value to 2500 oe.

On-state-loss data for the R-1 sample switches were taken at both 10 and 50 kilowatt maximum peak power levels. Data of this type are shown in Fig. 7, where on-state loss is plotted against incident peak power level. Notice that the loss increases rapidly as the incident peak power is increased and reaches a constant plateau value above 30 kw peak power. The parameter "plateau loss" (Fig. 7) refers to this plateau value and will be used in comparing the on-state nonlinear loss characteristics of the various switches.

Off-state-loss data were taken at both 10 and 50 kilowatt maximum power levels, and the range of applied field values (off-state field to 2500 oe) was covered in 125-oe increments. These data were used in constructing a plot of off-state loss as a function of applied field, with incident peak power as a parameter. Figure 8 is an example of this kind of plot.

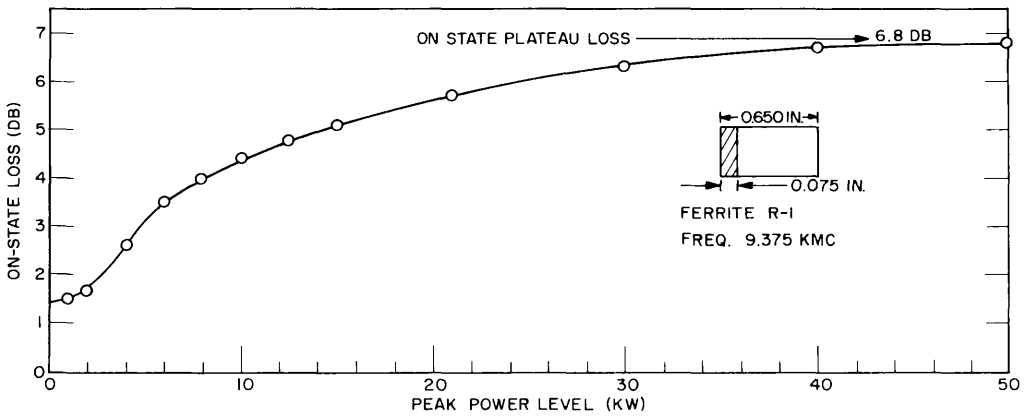

Fig. 7 - Typical high-power-level data, showing on-state loss as a function of incident peak power level

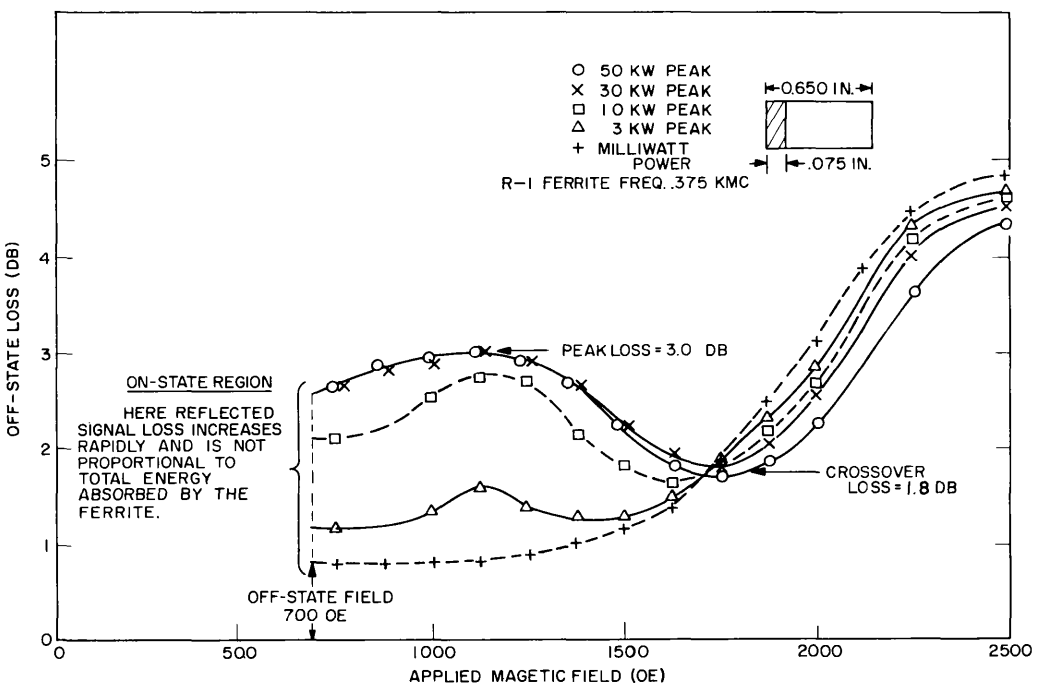

Fig. 8 - Typical high-power-level data, showing off-state loss as a function of applied magnetic field, with incident peak-power level as a parameter

Since the insertion loss is at least 30 db over the range of field values employed, off-state loss is substantially equivalent to the total energy absorbed in the ferrite section. Some interesting characteristics of the data should be noted. For example, notice the subsidiary resonance which appears near 1200 oe when the incident peak power exceeds the threshold level. Notice also that main resonance absorption is suppressed somewhat when the threshold power level is exceeded. Another characteristic is the "crossover region," which occurs between the subsidiary resonance and the main resonance. Over this very narrow region of applied field values, nonlinear loss is substantially eliminated. This kind

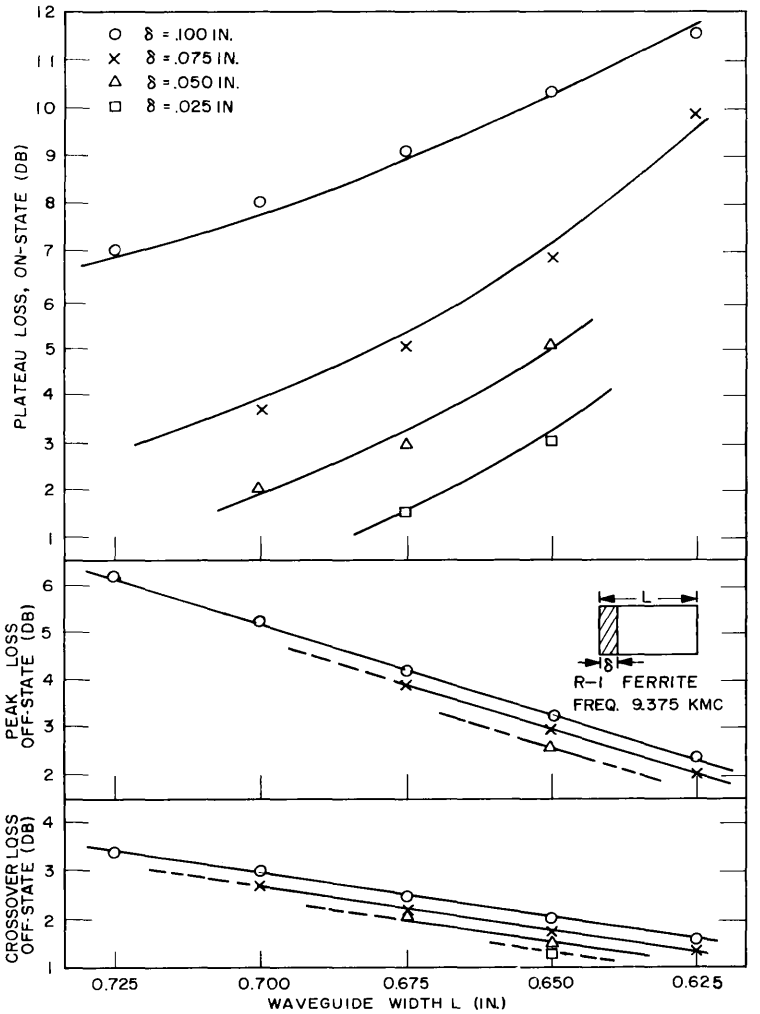

Fig. 9 - Dependence of nonlinear loss on waveguide width and ferrite slab thickness. Plateau loss, peak loss, and crossover loss are shown as a function of waveguide width, with slab thickness as a parameter.

of plot is typical of the data obtained for R-1 and TT2-125 sample switches and is described when the parameters peak loss and crossover loss (Fig. 8) are given. Peak loss refers to the maximum loss at 50 kw in the subsidiary resonance peak. Crossover loss refers to the loss associated with the crossover region.

Effect of Varying Waveguide Width

The dependence of on-state and off-state nonlinear loss on waveguide width was studied by varying the waveguide width while holding the ferrite slab thickness constant (Fig. 9). Plateau loss, peak loss, and crossover loss are given in Fig. 9 as a function of waveguide width, with ferrite slab thickness as a parameter. Notice that plateau loss increases when the waveguide width is reduced, while both peak loss and crossover loss decrease. Thus reducing the waveguide width causes off-state nonlinear loss to decrease and on-state nonlinear loss to increase. This phenomenon may possibly be explained in the following manner. In the on state, energy is transmitted through the ferrite-loaded

section. Reducing the waveguide width increases the ferrite internal energy density along its entire length and produces the observed increase in on-state nonlinear loss. In the off state, the switch acts as a shorted waveguide section and causes reflection. However, energy still penetrates into the ferrite region. When the waveguide is made more narrow, penetration into the ferrite region is reduced, causing the observed decrease in off-state nonlinear loss.

Effect of Varying Ferrite Slab Thickness

The dependence of on-state and off-state nonlinear loss on ferrite slab thickness was investigated by varying the ferrite slab thickness while holding the waveguide width constant. This dependence can be seen in Fig. 9. Notice that each of the quantities (plateau loss, peak loss, crossover loss) is reduced when the slab thickness is decreased. Thus both on-state and off-state nonlinear loss can be reduced by decreasing the ferrite slab thickness within the range of thicknesses for which an acceptable switch is defined.

Comparison of Single- and Double-Slab Switches

The high-power, nonlinear characteristics of switches composed of a single slab having thickness δ placed against a side wall were compared with those of switches composed of two slabs, each having thickness $\delta/2$, placed against opposite side walls. In particular, single-slab $\delta = 0.100$ in. switches and double-slab $\delta/2 = 0.050$ in. switches were compared, as were single-slab $\delta = 0.050$ in. switches and double-slab $\delta/2 = 0.025$ in. switches. Data were taken for three values of waveguide width: $L = 0.700$ in., $L = 0.675$ in., and $L = 0.650$ in. Plots of on-state loss as a function of incident peak-power level and off-state loss as a function of applied field (similar to Figs. 7, 8) were constructed for each of the twelve R-1 sample switches. Off-state nonlinear loss characteristics were evaluated by comparing the graphs of single-slab configurations with those of the corresponding double-slab configurations. These graphs were almost identical in every detail for each of the three values of waveguide width. On-state nonlinear loss characteristics were evaluated by comparing the plateau-loss values of the various single- and double-slab switches. The plateau-loss values of double-slab $\delta/2 = 0.050$ in. switches were significantly less than the corresponding single-slab $\delta = 0.100$ in. switches, while the double-slab $\delta/2 = 0.025$ in. switches showed very little reduction in plateau loss over the single-slab $\delta = 0.050$ in. switches. Also, the plateau-loss reduction of double-slab $\delta/2 = 0.050$ in. switches over single-slab $\delta = 0.100$ in. switches is greater for wider waveguides; the reduction varies from 5.0 db at $L = 0.700$ in. to 2.0 db at $L = 0.650$ in. Thus we see that, in general, the double-slab switch configuration provides a reduction in on-state nonlinear loss but causes no change in off-state nonlinear loss. The reduction in on-state nonlinear loss depends on waveguide width and ferrite-slab thickness; it increases with waveguide width and decreases when thinner slabs are utilized.

Effect of RF Heating

In conducting the high-power-level investigation, care was taken to minimize the rf heating of the sample switches. In this way it was hoped to separate variations in loss due to nonlinear effects from variations due to rf heating (thermal effects). Since in actual operation at high rf power this separation cannot be done, some indication of the effect of rf heating on switch loss is desirable. The effect of rf heating was observed by recording switch loss as the incident power was rapidly increased from zero to maximum power, allowing the switch to heat at maximum power until the loss reached a new stationary value, and then recording the loss as the power was rapidly reduced to zero. Both the on-state loss and the off-state loss of several sample switches were observed in this manner. Some general results of these measurements can be noted. At zero applied

field, rf heating tends to increase on-state loss by 2 to 4 db. Off-state loss is similarly increased over the range of applied field values from the off-state field value to the peak of the subsidiary resonance (approximately 1200 oe). Above the subsidiary resonance peak, the off-state loss is reduced, and the magnitude of this reduction increases as the applied field is increased into the main resonance region. At the subsidiary resonance peak there was no observed change in off-state loss due to rf heating. Above the subsidiary resonance peak, the observed loss due to rf heating (thermal effects) appears to be relatively independent of incident power level; i.e., if at a fixed field value (>1200 oe) a 1-db loss reduction is observed at 50 kw, the same reduction would be observed as the power is rapidly reduced to zero.

High-Power Characteristics of TT2-118 and TT2-125 Switches

On-state loss and off-state loss were recorded for the TT2-125 switches listed in Table 1. These data show the same general trends with respect to waveguide width and ferrite thickness as do the data for the R-1 switches, and the respective values of plateau loss, peak loss, and crossover loss have very nearly the same magnitude as the R-1 switches. In addition, a comparison of switches composed of a single δ = 0.100 in. slab with those composed of two δ = 0.050 in. slabs again showed the double-slab configuration to have significantly lower values of plateau loss, while the graphs of off-state loss as a function of applied field were essentially identical in every detail.

On-state and off-state losses were also recorded for the TT2-118 switches listed in Table 1 (single slab δ = 0.050 in., L = 0.675 in.; double slab $\delta/2$ = 0.050 in., L = 0.700 in.). At zero applied field and for peak power levels up to 100 kw, both switches had constant values of on-state loss. These values were 2.0 db and 2.5 db respectively. Neither switch showed a pronounced subsidiary resonance region. Several additional switches were observed, and in no case was a pronounced subsidiary resonance seen. A main resonance region was observed. The onset to the main resonance occurs at approximately 1250 oe.

The off-state loss value observed at 1375 oe for the single-slab (δ = 0.050 in., L = 0.675 in.) switch decreases slowly from 3.0 db at milliwatt power to 2.2 db at 100 kw peak power. This reduction results because the off-state field value (1375 oe) lies above the onset to the main resonance (1250 oe). This sort of reduction is characteristic of the main resonance region.

The off-state loss value observed for values of applied field from 750 oe to 1150 oe for the double-slab ($\delta/2$ = 0.050 in., L = 0.700 in.) switch increases from 1.8 db at 30 kw peak power to 2.1 db at 100 kw planar power. Compared with the R-1 and TT2-125 switches, the onset of nonlinearity of this switch occurs at a high peak power level, and above threshold the increase in loss with peak power level is moderate.

DISCUSSION OF RESULTS

Introduction

The results of this investigation will be discussed in terms of three kinds of applications – strictly low-power applications (below threshold), strictly high-power applications (above threshold), and applications involving operation at both high and low power. A radar antenna is an example of the latter kind of application. Switch characteristics to be discussed are on- and off-state bias fields, switch loss, and maximum bandwidth. Switch loss will refer to the sum of on-state loss and off-state loss (at a given bias field and power level). This represents the maximum loss due to either a single switch (assuming both the transmitted and the reflected signals are to be utilized) when it is switched

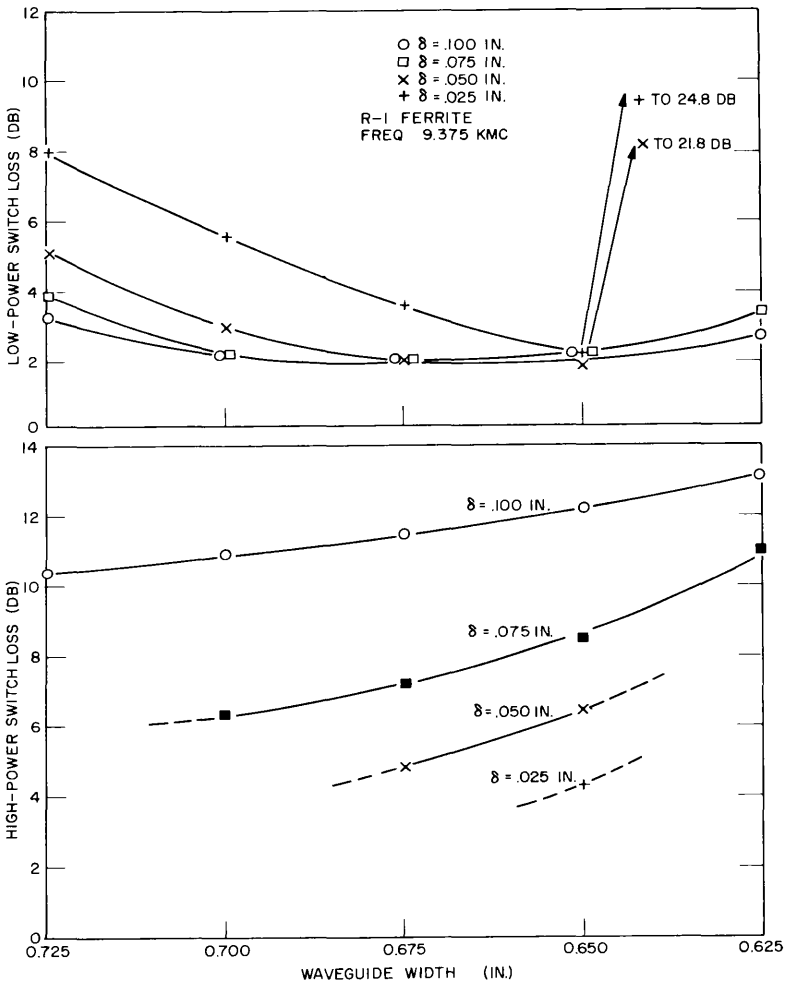

Fig. 10 - Dependence of low-power switch loss and high-power switch loss on waveguide width and ferrite slab thickness

alternatively between the on and off states, or a combination of two switches (one on state, one off state) used as a single switching unit. An example of the latter application is the reciprocal wye switch proposed by Soohoo.

Low-Power-Level Applications

For strictly low-power-level applications, on and off state bias fields should be chosen corresponding to minimum values of on-state loss and off-state loss. Minimum on-state loss occurs at zero applied field, while the field value at which minimum off-state loss occurs depends on switch geometry. Low-power switch loss, then, is defined as the sum of minimum on-state loss and minimum off-state loss. Figure 10 shows a plot of low-power switch loss as a function of waveguide width, with ferrite slab thickness as a parameter. The optimum switch configurations are indicated by ranges of waveguide widths for which low-power switch loss has its minimum value. These ranges all occur in the region of waveguide widths L greater than the cutoff value L_c.* The minimum value

*See note on p. 1

of low-power switch loss (approximately 2.0 db) is relatively independent of slab thickness, but the thicker slabs can be used with a broader range of optimum-width waveguides, while thinner slabs can be used with only a very narrow range. For example, the δ = 0.100 in. slab has minimum low-power switch loss over the range $0.700 \geq L \geq 0.640$ in., while the δ = 0.025 in. slab is restricted to a range in the close vicinity of L = 0.650 in.

Low values of off-state bias field and operation over a broad band of frequencies are desirable characteristics. If one considers only values of waveguide width L greater than the cutoff value of waveguide width L_c,* off-state field can be reduced either by decreasing the waveguide width L or by increasing the ferrite slab thickness δ. The lower and upper frequency limits of maximum bandwidth are defined by the values of cutoff frequency that occur at zero field and 1250 oe respectively. Maximum bandwidth is independent of waveguide width, but it can be increased by using thicker ferrite slabs. In order to optimize switch operation with respect to maximum bandwidth or off-state bias field, the switch having the thickest slab and a value of off-state field $\leq$ 1250 oe should be used. Off-state bias must lie in the range off-state field $\leq H_a \leq$ 1250 oe. The broadest possible bandwidth is achieved by choosing 1250 oe as the bias field. Reducing the bias below this value will cause the maximum bandwidth to be reduced. Operation at a bias field less than the off-state field value is not defined. These conditions are met best by switches using thick slabs in more narrow waveguides (i.e., δ = 0.100 in. or δ = 0.075 in. and L only slightly greater than L_c).

The general low-power characteristics of the Trans Tech switches were the same as the R-1 switches. Switches TT2-125 exhibited approximately the same loss as the R-1 switches. Switches TT2-118 exhibited prohibitively high values of on- and off-state loss.

High-Power-Level Applications

For strictly high-power-level applications, on- and off-state bias fields which tend to minimize nonlinear loss should be chosen. On-state nonlinear loss is minimum at zero applied field. Off-state nonlinear loss is eliminated at the "crossover point." High-power switch loss can be defined as the sum of plateau loss and crossover loss. Figure 10 shows a plot of high-power switch loss as a function of waveguide width, with ferrite slab thickness as a parameter. Taken separately, plateau loss increases when the waveguide width is reduced, while crossover loss decreases, so that one can be enhanced only at the expense of the other. High-power switch loss, however, is seen to decrease as the waveguide width is increased. For a fixed-width waveguide, both plateau loss and crossover loss can be reduced by decreasing the ferrite slab thickness. Thus the sum of these parameters, high-power switch loss, also is reduced. It should be noted here that switches consisting of two $\delta/2$ slabs exhibit significantly less high-power switch loss than the corresponding single-slab switches. The observed loss difference is less when thinner slabs are used.

A low value of off-state bias field is desirable. However, in order to minimize off-state nonlinear loss, a bias field corresponding to the crossover point was chosen. The crossover point occurs at approximately 1700 oe for R-1 switches and does not change significantly with waveguide width or slab thickness. Thus the off-state bias field can be reduced below the crossover point only if one is willing to take the increased off-state nonlinear loss.

Operation over a broad band of frequencies is a desirable characteristic. Since the high-power-level off-state bias field is 1700 oe (the crossover point) rather than the low-power-level maximum of 1250 oe, the high-power-level values of maximum bandwidth should be somewhat larger than the corresponding low-power-level values given in Fig. 5. Also, the high-power-level values should continue to be independent of waveguide width

*See note on p. 1

and to decrease with decreasing ferrite-slab thickness. It should be noted that while the use of thin ferrite slabs tends to reduce high-power switch loss, it also tends to reduce maximum bandwidth.

The two TT2-118 switches had the best high-power characteristics of any switches tested. These switches exhibit no nonlinear loss in the on state and only moderate nonlinear loss in the off state. The rather high loss values observed at low-power level were reduced to an acceptable level either by thermal or nonlinear effects (or a combination of these effects). The TT2-125 switches exhibited the same high-power characteristics with respect to waveguide width, slab thickness, and single-double slab comparison as the R-1 switches. The values of plateau loss and crossover loss were also approximately the same as in the R-1 switches.

Applications Involving Both High and Low Power

The off-state bias fields which provide the lowest values of loss for high- or low-power applications are in general different. Off-state loss is minimized in low-power applications by operating below the main resonance region, and in high-power applications it is minimized by operating at the crossover point, 1700 oe, which lies just above the onset to the main resonance region. Thus in a radar application, for example, one may not be able to design a switch which when operated at a single off-state bias field will minimize the loss in both the outgoing high-power signal and the low-power echo signal. This can be seen by observing the off-state loss (Fig. 8) corresponding to milliwatt power and 50 kw peak power.

One solution to this problem would involve changing the off-state bias field, following transmission and before reception, from the crossover point to the low-power-level value. If this change can be made fast enough, this solution could be practical. Otherwise one may wish to select a compromise design which at a single value of off-state bias field would minimize the round-trip switching loss; i.e., the sum of the losses seen by high- and low-power signals in both the on and off states. In selecting a compromise switch design, three parameters will be considered: on-state bias field, off-state bias field, and switch configuration.

Compromise values of on-state bias field and off-state bias field will be chosen so as to minimize the sum of either high- and low-power on-state loss, or high- and low-power off-state loss. Both high- and low-power on-state loss are minimized at (or very near) zero applied field, and the sum of these losses would also be a minimum. Zero applied magnetic field can be chosen as the compromise on-state bias field. The compromise value of off-state bias field can be found by plotting the sum of low-power off-state loss and high-power off-state loss against the applied magnetic field. On such a plot the minimum value of this sum can be readily seen and would indicate the compromise value of the off-state bias field. This value should be very near the crossover point, and it should be relatively independent of switch configuration.

A compromise switch configuration which would have the lowest value of round-trip switching loss can be selected by calculating the sum of high- and low-power on-state loss and high- and low-power off-state loss. Only switch configurations meeting the conditions $L - \delta \leq L_c$ and $L \geq L_c$ need be considered. These calculations were made for R-1 switches operated at milliwatt power and 50 kw peak power. The $L = 0.650$ in., $\delta = 0.025$ in. configuration had the lowest value of round-trip switching loss. This result should not be surprising. This switch is one of those having a minimum value of low-power switch loss and, because it is the thinnest slab investigated, it has the lowest value of high-power switch loss. Thin slabs absorb less power.

SUMMARY

In this study the fact that both high- and low-power switching characteristics depend on switch geometry (i.e., waveguide-ferrite configuration, and the variety of ferrite used) has been demonstrated.

When one can operate below the threshold for nonlinear loss, a reasonably good switch can be designed using low-loss ferrites (e.g., R-1 and TT2-125). At the fixed frequency of 9.375 kMc, these switches should be operated between zero field (on state) and the off-state bias field corresponding to minimum off-state loss. For a fixed slab thickness, low-power switch loss has a minimum value over ranges of waveguide widths L, all of which are greater than the cutoff value L_c.* This minimum value of switch loss is the same for each ferrite slab thickness observed. Within these ranges of optimum-width waveguides, bandwidth can be increased and bias field reduced by using the thick ferrite slabs in the more narrow waveguide.

When operation at high power levels is anticipated, a ferrite having a high threshold for nonlinear loss should be used (e.g., TT2-118). However, when the threshold must be exceeded, nonlinear loss can be reduced by operating the switch between zero field (on state) and the crossover point (off state). At the crossover point, off-state nonlinear loss is essentially eliminated. From the point of view of switch configuration, the use of the thinnest slab in the widest possible waveguide (subject to the conditions $L - \delta \leq L_c$ and $L \geq L_c$) will reduce the high-power switch loss. Also, in general, the double-slab ferrite configurations exhibit less high-power switch loss than the corresponding single-slab configurations. This loss reduction is more significant when thick slabs are used. Finally, high-power-level rf heating was observed to reduce off-state loss when the off-state bias field exceeded the value corresponding to the peak of the subsidiary resonance.

When a switch is subjected to both high- and low-power-level rf signals (radar-type applications), a compromise design can be selected. Zero-field on-state bias and off-state bias near the crossover point seems to be indicated. These fields will minimize the sum of high- and low-power on-state loss and high- and low-power off-state loss respectively. A compromise switch configuration can be selected by summing high-power on-state loss, low-power on-state loss, high-power off-state loss, and low-power off-state loss and choosing the configuration having the lowest sum. The R-1 configuration so selected was the single $\delta = 0.025$ in. slab in a $L = 0.650$ in. waveguide.

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*See note on p. 1.

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The characteristics of the Soohoo-type cutoff switch have been measured at X band. Two types of switch configuration were employed; in one, a single ferrite slab was placed against a waveguide sidewall, and in the other two ferrite slabs were placed against opposite sidewalls. The switch is made to operate between an "on state" (or propagation state) and an "off state" (or reflection state) by application of a transverse magnetic field to the ferrite. This action reduces the effective waveguide width and causes cutoff.

Low-power-level switching characteristics were studied as a function of switch geometry, and a group of switches meeting minimal specifications were selected for study at high-power level. The effect of varying waveguide width, the variety of ferrite used, and the width of the ferrite slab on nonlinear loss were studied at high-peak-power level as a function of applied magnetic field. Some techniques which tended to reduce nonlinear loss were noted.

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