waveguide, and the resulting value of β_1 was determined with the aid of a method described by the author elsewhere.[6] The thickness of the dielectric sheet to give the necessary value of $\beta_2=\beta_1$ was determined from the transverse resonance condition.[1a] Because of inaccuracies involved in this procedure, the design did not result in the desired situation in which $\beta_2=\beta_1$ at the design frequency. At this stage, use has been made of the fact that the group velocities in the coupled lines have different values, *i.e.*, $\partial\omega/\partial\beta_1 \neq \partial\omega/\partial\beta_2$, and by searching in the neighborhood of the design frequency, a particular frequency has been found for which $\beta_1=\beta_2$.

Copper-clad teflon, and later Rexolite, have been used in the construction of the reactive surface. The coupling aperture consisted of a row of 150 slots cut in the wide wall of a 0.4×0.9-in ID rectangular waveguide (see Fig. 2). The measurement of the field amplitude in the waveguide was performed by cutting in the opposite wide wall a longitudinal slot such as used in a slotted section and mounting the waveguide in a hp809B Universal Probe Carriage from which the original slotted section has been removed. The whole setup has been placed on a surface covered with microwave absorbing material.

In a few experiments conducted up to now, excitation efficiencies of between 92 and 95 per cent have been determined.

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Higher-Order Mode Resonances in Strip-Line *Y*-Junction Circulators*

Because of its small physical size, the *Y*-junction circulator has been the recipient of a great amount of investigation. Various theorists and experimentalists have devoted time to understanding the behavior of this device, both on the far and near side of ferrimagnetic resonance.[1–4]

In our laboratory, we have succeeded in developing units operating at the near side of resonance from 1.0–8.0 kMc. These units have instantaneous bandwidths providing 20 db of isolation in excess of 20 per cent; some units have bandwidths as high as 40 per cent. One of the limitations on bandwidth that we have discovered are resonances that occur in the insertion loss and isolation characteristics of the device at the HF end of the band. In narrow-band designs, these resonances might never be noticed. Because of their presence, it is necessary to limit the bandwidth specification to exclude them from the operating region. If resonance could be eliminated, we believe bandwidths of 50–60 per cent could be achieved.

Fig. 1 shows some experimental points relating the frequency at which the resonance occurs to the diameter of the ferrimagnetic material used in the design. Various materials were used, and they are labeled with their manufacturer's designation.

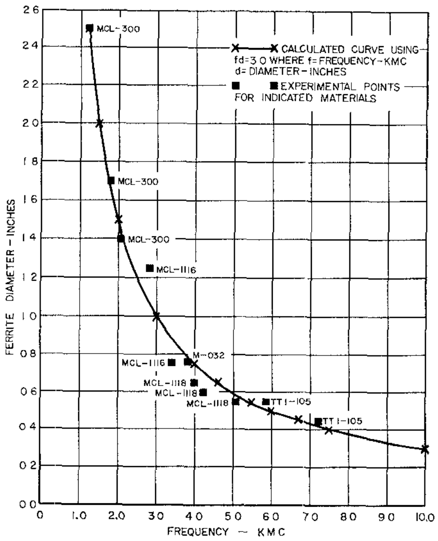

Fig. 1—Diameter at which higher-order mode resonance occurs for strip-line *Y*-junction circulators on the near side of resonance.

The frequency of these resonances depends upon the value of magnetic field. They occur at lower frequencies for smaller field values. The values of field used in the data presented were sufficient to saturate the disks.

A theoretical curve is plotted using the relationship

$$fd=3.0$$

where

f=frequency in kMc
d=diameter of material in inches.

This type of expression is typical of propagation in cylindrical waveguide where the mode cutoff frequency is related to the guide diameter and the proper-order Bessel function. It is felt, therefore, that these resonances can be explained by higher-order mode propagation in a direction parallel to the applied magnetic field, even though the dominant mode in the strip line is propagating perpendicular to this direction.

It is hoped that these resonances can be moved to higher frequencies without effecting the basic nonreciprocal scattering of the ferrimagnetic disks. Experiments to determine the feasibility of removing these resonances are now underway and, if successful, will be reported.

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* Received by the PGMTT, August 21, 1961.

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A Proposed Design to Enhance Microwave-Power-Limiter Characteristics*

A design is proposed for a device which would enhance the properties of presently available microwave power limiters, thereby making their use as crystal protectors in duplexing units of microwave systems more desirable. This design is a combination of a power-sensitive, nonlinear element with a traveling-wave ring resonator.

Several nonlinear elements, such as subsidiary resonance ferrite limiters,[1] and DeGrasse type of ferrimagnetic limiters,[2] and diode parametric limiters[3] have been devised which exhibit an attenuation vs power-level curve such as is depicted in the lower curve of Fig. 1. The nonlinear properties of ferroelectric materials indicate that these materials might also be used to produce limiting action.

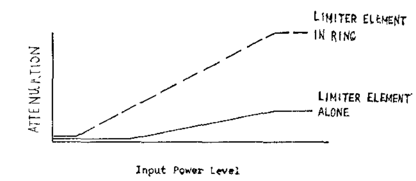

Fig. 1.

However, the referenced limiters are not completely usable as crystal protectors because either their threshold power levels are too high, or their maximum attenuations, slopes of attenuation vs power curve, or their power-handling capabilities are inadequate. Combining any one of the nonlinear elements with the traveling-wave ring resonator would improve upon all of these shortcomings, provided that the low-level insertion loss of the element is sufficiently small.

* Received by the PGMTT, August 21, 1961.

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Much has been written about the traveling-wave ring resonator.[4–6] Its properties, particularly the rapidity of the decrease in amplification factor with increasing ring attenuation, are relatively familiar. If a second coupler is added to the ring circuit to couple power out, it may be used as a passband-stopband filter for frequency separation and combination.[7]

Consider the microwave circuit in Fig. 2; this is a traveling-wave ring-resonator comprised of two directional couplers. Two ports of each coupler are joined to form an integral wavelength transmission line into which a power-sensitive, nonlinear element, having an attenuation vs power-level characteristic (such as in Fig. 1), has been introduced.

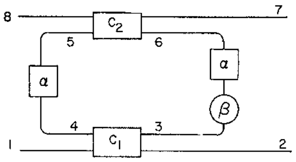

Fig. 2.

where

α = attenuation of one-half of ring circuit

a = transmission constant corresponding to α, ($a = 10^{-\alpha/20}$)

β = attenuation of limiter element, a function of E_3, ($\beta = f(E_3)$)

b = transmission constant corresponding to β, ($b = 10^{-\beta/20}$)

C_1 = coupling coefficient of input directional coupler

$$E_3/\underline{\theta_3} = C_1 E_1/\underline{\theta_1 + 90°}$$

$$E_2/\underline{\theta_2} = \sqrt{1 - C_1^2}\; E_{1/\theta_1}$$

C_2 = coupling coefficient of output directional coupler

$$E_8/\underline{\theta_8} = C_2 E_6/\underline{\theta_6 + 90°}$$

$$E_5/\underline{\theta_5} = \sqrt{1 - C_2^2}\; E_6/\underline{\theta_6}$$

An analysis has been made which shows that the voltage amplification factor or the ratio of RF voltage in the ring to that in the input transmission line is

$$\frac{E_3}{E_1} = \left| \frac{E_3/\underline{\theta_3}}{E\theta_1/\underline{_1 + 90°}} \right| = \frac{C_1}{1 - a^2 b \sqrt{1 - C_1^2}\sqrt{1 - C_2^2}}, \quad (1)$$

and the transmission through the device, from port 1 to port 8 is

$$\frac{E_8}{E_1} = \left| \frac{E_8/\underline{\theta_8}}{E_1/\underline{\theta_1 + 90°}} \right| = \frac{abC_1C_2}{1 - a^2 b \sqrt{1 - C_1^2}\sqrt{1 - C_2^2}}. \quad (2)$$

For any given value of $a^2 b_0$, where b_0 is the maximum value of b under low-power level and minimum insertion-loss operation, the condition may be imposed by judicious design that

$$\sqrt{1 - C_1^2} = a^2 b_0 \sqrt{1 - C_2^2}. \quad (3)$$

If this condition is met, it may be shown that $E_2 = |E_2\, /\underline{\theta_2}| = 0$, due to destructive cancellation in arm 2. Assuming highly directional couplers and matched components are used throughout, all power incident to port 1, less insertion loss in the ring circuit and limiter element, emerges from port 8. For high-power operation, where limiting is desired, b becomes very small. Eq. (3) is no longer satisfied, and most of the incident power goes to the matched load on port 2. It may be shown that the power incident to the limiter element is less than that at port 1 by a factor approaching the decoupling value of directional coupler number 1. This results in an equal increase in the power-handling capability of the device over the limiting element used alone.

For low-power level operation, where b is very nearly unity (leftmost section, Fig. 1) and (3) is satisfied, (1) and (2) reduce to

$$\frac{E_3}{E_1} = \frac{1}{C_1}, \quad (4)$$

and

$$\frac{E_8}{E_1} = \frac{abC_2}{C_1}, \quad (5)$$

respectively.

Under these conditions, the power level in the ring circuit, which is the power incident to the limiter element, is $(1/C_1)^2$ times greater than the power in port 1. The device will reach its threshold at a power level $(1/C_1)^2$ times less than the threshold of the limiter element.

At high-power levels, the isolation between port 1 and port 8 approaches the sum of the isolation of the limiter element and the decoupling factors of both direction couplers [see (6)]. This can be seen intuitively in Fig. 2 by removing the section of the ring circuit opposite the limiter element. This may be done at power levels at which the attenuation of the limiter element is high, since very little power (approaching zero for sufficiently high attenuations) is carried by this transmission line. It is obvious from the circuit, then, that

$$E_8/E_1 = C_1 b C_2. \quad (6)$$

An absorptive limiter would be more easily used as a crystal protector since a reflective limiter would necessitate the use of a circulator or isolator to get rid of the unwanted leakage power and to provide transmitter isolation. Since most limiter elements are reflective in nature, the proposed device will provide an additional advantage in that the input VSWR will be reduced from nearly infinity to a value approximately that of a short circuit viewed through an attenuation equal to the decoupling factor of the input directional coupler. This would make the problem of transmitter isolation less severe.

It is felt that 0.1 db is an attainable figure for low-level insertion loss for a crossed-stripline ferrimagnetic limiter at S-band frequencies, which includes limiter-element loss and transmission-line loss. This figure would correspond to $2\alpha + \beta$, making $a^2 b$ equal to 0.98953.

Starting with this assumption, typical design figures might be as follows: Choosing a value of 7.0 db for the input coupler, $C_1 = 0.445$ and $\sqrt{1 - C_1^2} = 0.896$. To satisfy (3) and enforce optimum operation at low-power levels, $\sqrt{1 - C_1^2} = a^2 b \sqrt{1 - C_2^2}$, $\sqrt{1 - C_2^2} = 0.9053$, $C_2 = 0.424$, and the output directional coupler-decoupling factor is seen to be 7.5 db. For low-power level operation, $E_8/E_1 = abC_2/C_1 = 0.948 = 0.45$ db, which is an increase of 0.35 db over the limiter element above. The power buildup factor, $P_3/P_1 = (E_3/E_1)^2 = (1/C_1)^2 = 5.05 = 7.0$ db, reduces the effective threshold of the device by 7.0 db below that of the element alone.

For operation above threshold power levels where $a^2 b$ is no longer nearly unity, (3) is no longer satisfied, and the isolation through the device becomes

$$\frac{E_8}{E_1} = \frac{abC_1C_2}{1 - a^2 b \sqrt{1 - C_1^2}\sqrt{1 - C_2^2}} = \frac{0.1877b}{1 - 0.8028b} = \frac{0.1877(10^{-\beta/20})}{1 - 0.8028(10^{-\beta/20})},$$

where β is the attenuation of the limiter element in db. It is seen that a slight change in β has a great effect on transmission loss E_8/E_1 providing effective "amplification" of limiting attenuation. As the attenuation of the limiter element increases and oscillations in the ring circuit are greatly reduced, the power incident to the limiting element is 7.0 db below the input power, raising the power-handling capability of the device 7.0 db above the limiter element alone. The isolation through the device approaches a value of 14.5 db greater than the limiter element isolation for increasing power levels. The maximum input VSWR is 1.50:1, when the limiter element is infinitely mismatched.

The preceding typical design figures could be still further improved by using more strongly decoupled directional couplers, but only at the expense of increased low-level insertion loss.

It is felt that the foregoing proposal has sufficient merit to warrant further investigation, and an experimental study is planned.

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