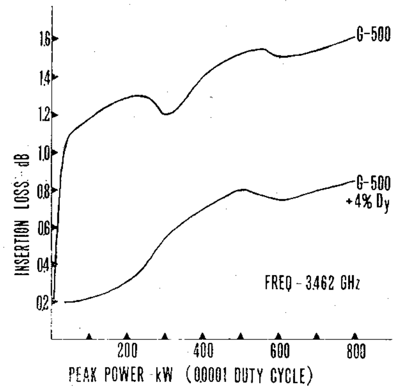

Fig. 3. Insertion loss versus peak power for various ferrites.

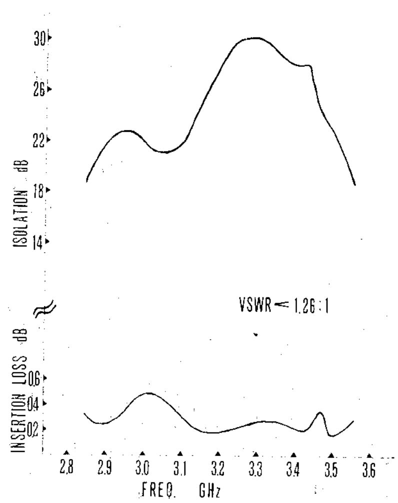

Fig. 4. Circulator operating characteristics.

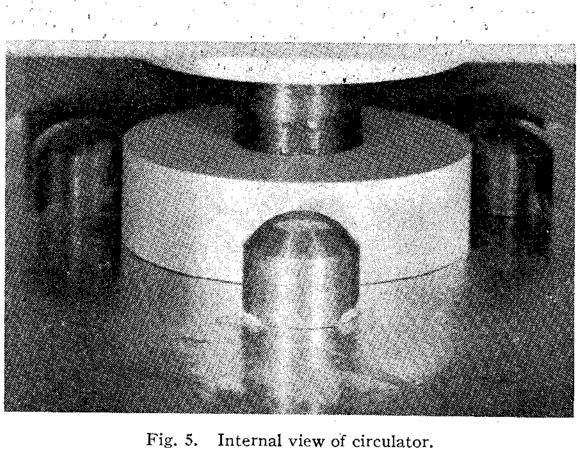

Fig. 5. Internal view of circulator.

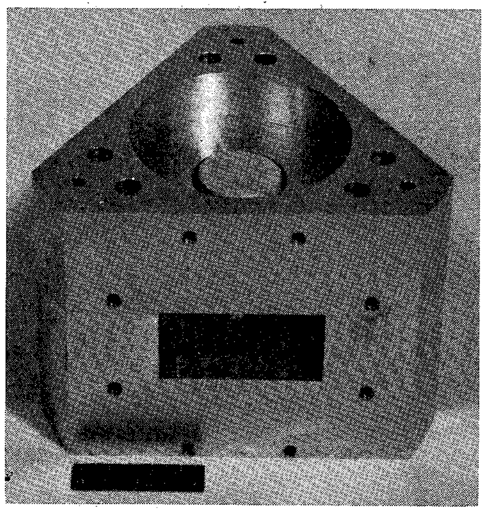

Fig. 6. Circulator configuration.

housing, the overall microwave high-power operating characteristics could be further improved by this more efficient removal of heat from the junction region. Fig. 5 is a view of a portion of the junction region showing ferrite, boron nitride matching transformer, and capacitive tuning buttons. Fig. 6 is an overall view of the circulator.

Conclusion

The successful design of this high-power S-band circulator clearly demonstrates that, in many cases, a large heavy-differential phase-shift circulator or narrow-band junction circulator can be replaced by this H-plane Y-junction circulator. This unit is substantially smaller in size and weight than a differential phase-shift-type device, and also spans a broader bandwidth than state of the art junction circulators available at these frequencies and power levels. By incorporating cooling fins in the junction housing, one could operate this device at power levels up to 1-MW peak, and 1-kW average, without significantly affecting the operating characteristics of the circulator.

Acknowledgment

The author wishes to thank J. Agrios for adapting and programming the computer analysis which was initially used to design the model, J. LoCicero for his invaluable assistance in fabricating the experimental models constructed during the course of this investigation, and C. Heinzman for his valuable assistance in the area of high-power testing.

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The Digital Twin-Ferrite-Toroid Circular Waveguide Phaser

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Abstract—A new microwave structure is proposed, consisting of a circular waveguide loaded with two ferrite toroids circumferentially magnetized at remanence in opposite direction. It is shown that nonreciprocal parameters such as differential phase shift can be doubled with respect to the single toroid configuration. A method for biasing the toroids at remanence in opposite directions by means of a single wire passing through the axis of the waveguide is proposed.

Modal purity is taken into account in order to select dielectric loading parameters which ensure operation within the modal inversion window in which the TE_{01} mode is dominant. The propagation factor and differential phase shift are computed under these conditions, and their variation with several parameters such as remanent magnetization, toroid location, and toroid thickness is shown.

Introduction

There are at present no exact solutions for the geometries used in several ferrite devices primarily because the exact form of the device entails solving an extremely complex field theoretic problem, while

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even idealizations alleviate the difficulty only somewhat. An exception to this situation is the circular guide loaded with circumferentially magnetized ferrite tubes. Here the model and the exact device geometry coincide; nevertheless, little interest has been shown to date on the configuration. The reason for this seems to be that device operation depends on the excitation of the TE_{01} circularly symmetric mode, which is not the fundamental mode to propagate through the guide. Recent research has shown that a solution to this problem is available, and guided wave propagation with azimuthally magnetized ferrites has consequently been re-examined in some detail.

It was early recognized that the advantage of azimuthal magnetization of toroids in circular guides over toroids in rectangular guides is that all the ferrite material inside the circular waveguides may be arranged to interact maximally with the RF field. The purpose of this study is to explore theoretically the dependence of the nonreciprocal properties of the toroid loaded circular waveguide with different ferrite parameters. Attention is restricted to the major nonreciprocal parameter, namely, differential phase shift. The results of this study will be especially relevant to nonreciprocal digital remanence phase shifters, although the general theoretical principles can be applied to other types of nonreciprocal devices. For earlier work on the related simple toroid structure consult [1] and [2].

Nonreciprocity

In a circular waveguide transmitting the TE_{01} mode, the loci where the h field is circularly polarized are two concentric cylinders of radii r_1 and r_2 (Fig. 1). If a ferrite toroid magnetized in the $+\phi$ direction is placed at r_1, and if we assume for the moment that the fields are not severely distorted, we see that the RF h field is against the precession of the electron spins for a wave propagating in the $+z$-direction; the resultant effective permeability will be different than the effective permeability for a wave propagating in the $-z$-direction, because the latter has its h-field polarization precessing in the same sense as the electrons. Consequently, the waves will have different propagation constants and field distribution. Alternatively, if the direction of magnetization of the toroid is reversed, the propagation constants will be interchanged: reversal of magnetization is equivalent to interchange of propagation directions; therefore, if only the $+z$-direction of propagation is considered, reversal of ferrite magnetization will bring about a change in the propagation factor. This nonreciprocity is accentuated as the difference of the effective permeabilities is increased when the magnetization is reversed.

It was already suggested by Fox, Miller, and Weiss [3] that nonreciprocity could be increased if two ferrite toroids, magnetized in opposite directions, were placed at r_1 and r_2, because the interaction with the electron spins is considerably increased (Fig. 1). This is "equivalent" to loading a rectangular waveguide with two oppositely transversely magnetized ferrite slabs.

Curves showing the differential phase shift versus toroid location for only one toroid inside a circular waveguide are given in [1], [4], [5]. If two toroids with opposite magnetization are placed at the radii corresponding to the peaks of these curves, approximately twice the differential phase shift obtained with one toroid will result. At the same time, the ferrite losses will also double. If this structure is used as a nonreciprocal phase shifter, the figure of merit f_1 (degrees of differential phase shift/loss dB) will not deteriorate, and the figure of merit f_2 (differential phase shift/insertion phase) will improve roughly by a factor of two.

An added advantage would be the possibility of operating the structure in four states of magnetization, two with the toroids magnetized in opposite directions and two with the toroids magnetized in the same direction, although, to date, it has not been established that the design parameters can be arranged to yield suitable or desirable phase relations between these four states.

The structure can also be used as field displacement isolator [2], and its performance can also be expected to improve with respect to the one-toroid waveguide.

Biasing the Toroids

The twin-toroid guide can be used as a remanent device or with a holding current that creates a steady H_{dc} circumferential field. In both cases, the problem of biasing the toroids with an H_{dc} field in opposite directions is of prime importance. The following basic method is to be preferred. (See Fig. 2.)

A biasing wire passes through the axis of the waveguide as in the single-toroid case. The biasing current creates a circumferential H_{dc} field, which has the same direction at both toroids. Making use of the square loop hysteresis properties of the ferrite toroids, it is possible to magnetize the toroids at remanence with opposite circumferential magnetization. The method closely resembles the so-called "partial switching" method studied by R. H. Taverell and R. E. MacMahon [6] for ferrite memory cores, and applied by H. Hair [7] to helical phase shifters; it is also explained in detail by W. J. Ince and D. H. Temme [8].

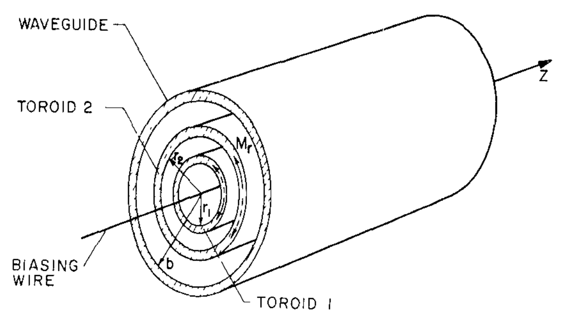

Fig. 1. The twin-toroid geometry.

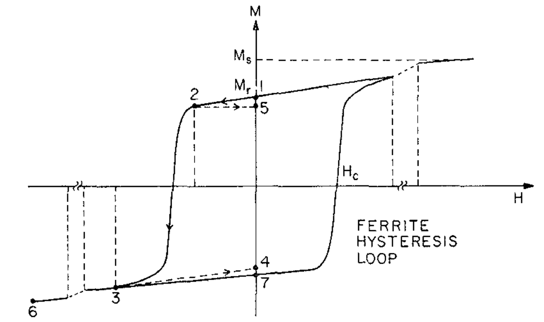

Fig. 2. Hysteresis loop and magnetizing cycle of the ferrite toroids.

The method is based on the $1/r$ dependence of the applied H_{dc} field; the field at r_1 is (r_2/r_1) times the field at r_2. Suppose that both toroids are initially at point 1 of the loop, that is, magnetized at remanence in the same direction; a negative current pulse is applied to the wire, its amplitude being such that the applied H_{dc} field at toroid 2 lies just before the "knee" of the loop (point 2), while toroid 1 is at point 3. After the pulse, toroids 1 and 2 will go to points 4 and 5, respectively, along the path showed by the dotted lines. The toroids are then at remanence, with opposite magnetizations. To simultaneously change both magnetizations, a strong negative reset current pulse is sent through the wire, and then the whole process may be repeated with opposite polarity.

The success of this method depends on whether the ferrite loops have enough "squareness" for a given r_2/r_1 ratio. This ratio cannot be made arbitrarily large, since the toroids's location will be governed, in general, by operating factors such as maximum differential phase shift.

When the small current pulses are applied, the inner toroid goes through an irreversible process, whereas the outer toroid goes through a reversible one. The magnetization energy required during the short pulse will therefore be less than twice the energy required for one single toroid while the energy required during the rest pulse will be approximately twice the energy required for a single toroid. It is then clear that between three and four times more energy will be needed to switch this configuration than for one toroid case. The switching time is also increased by a factor of 2, approximately.

The partial switching method used in helical phase shifters is somewhat similar; the advantage of using two toroids is two-fold: first, less ferrite material is used (thereby decreasing magnetic losses); second, loop squareness increases when the toroid thickness decreases since the shell model can be applied to any toroid, even "thin" toroids, and the hysteresis loop is actually an average of the loops of each shell constituting any "thick" toroid.

Differential Phase Shift under Conditions of Modal Inversion

As mentioned before, the device operation rests on the assumption that the TE_{01} mode propagates through the waveguide. If other modes are present, degradation of performance can be expected to occur. It is, therefore, extremely important to retain modal purity.

To obtain modal inversion dielectric loading needs to be employed which, in any case, will have to be used in any practical device to provide mechanical support to the toroids, for heat removal, etc. To select the appropriate type of dielectric loading, we can see that a general type of structure (Fig. 1) may incorporate up to three different dielectric regions, plus the two ferrite toroids. It is, therefore, necessary to consider at least eight parameters to allow optimization of any nonreciprocal property such as differential phase shift. Thus it is necessary to devise some method of attack which is simple, yet useful, to determine the influence of each parameter in the behavior of the structure.

To have modal inversion, the center dielectric must have a permittivity larger than the outer dielectric (air, unless otherwise specified) and the unloaded waveguide must be below cutoff. As the regions near the guide wall are loaded, the window width decreases and eventually disappears.

The selection of frequency and dimension for window operation depends on the device under consideration. We start our analysis by choosing the range of parameters which ensure maximum window bandwidth when operating at the window center. The following sets of parameters are taken from [2]:

	b_1/b	b/λ_0	ϵ_1/ϵ_0	b_1/λ_0
1.	0.23	0.20	120	0.046
2.	0.30	0.18	80	0.054
3.	0.40	0.173	50	0.0692
4.	0.48	0.176	30	0.0845

Before examining the exact solution, we would like to have an indication of where to place the toroids for maximum differential phase shift. It is evident that their approximate position should be at the location where the h field is circularly polarized, i.e., at radii r_1 and r_2. Consequently, we need to know the variation with r of the ratio $|H_r/H_z|$ (TE_{01} mode) and, specifically, the values of r for which this ratio equals 1. The loci of circular polarization were computed for various dielecting loading and it was found that one locus falls within the dielectric loading cylinder, whereas the other falls outside it. The ratio r_2/r_1 decreases as the permittivity of the dielectric loading decreases, as shown in the following table:

	r_2/r_1	ϵ_1/ϵ_0	r_1/λ_0
1.	5.16	120	0.030
2.	3.46	80	0.038
3.	2.47	50	0.048
4.	1.68	30	0.052

The permittivity of the dielectric loading corresponding to the second set of parameters was 80, and we see that a reasonable value of r_2/r_1 is attained in this case. As pointed out by Ince and Tsandoulas [2], materials such as rutile ($\epsilon'=80$) might be used, and with $r_2/r_1 \geq 3$, a variety of ferrite materials are available with an adequate hysteresis loop.

To compute the differential phase shift for any given set of parameters, it is necessary to find the propagation factors for the two states of remanent magnetization. In accordance with the results of the previous section, the structure to be analyzed is shown in Fig. 3. Losses are neglected, and variation of the type exp $(j\omega t - j\beta z)$ is assumed throughout and suppressed. Both toroids have the same thickness, δ, and the arrows within them show the direction of magnetization for the first state; it is reversed in both for the second state. The corresponding propagation factors are β^+ and β^-. The gyrotropic medium is characterized following the convention given in [12].

The fields in the isotropic regions are expressed in terms of Bessel and Neumann functions. Only TE_{0n} modes are considered, i.e., $\partial/\partial\phi \equiv 0$. Under these circumstances, the fields in the anisotropic regions have been analyzed by Suhl and Walker [9], Bolle and Heller [1], Ince and Tsandoulas [2], and Bernues and Bolle [10]. The details of the calculation of the propagation factors and the differential phase shift for the structure of Fig. 3 are described in [11].

Computations were made for the following parameters:

$$b/\lambda_0 = 0.18$$

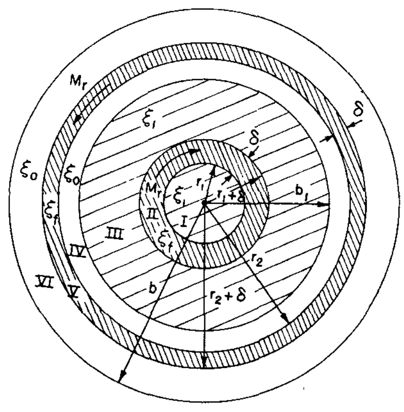

Fig. 3. The twin-toroid dielectric loaded circular waveguide.

$$b_1/\lambda_0 = 0.064$$

which correspond to the previously introduced "second set of parameters," with $\epsilon_1 = 80$.

Note that the value of b_1 has been increased by an amount equal to δ, in an attempt to offset the effect of the intercalation of the inner toroid. ϵ_f was fixed at 15 throughout the computations. The thickness of the toroids was taken as $\delta/\lambda_0 = 0.01$ and the remanent magnetization such that $\kappa = \pm 0.3$.

With these parameters, the outer toroid was placed at the value of r_2 given by the results of the previous section, i.e., $r_2/\lambda_0 = 0.128$.

The inner toroid position was varied around the value of r_1 obtained from the circular polarization loci values. For each position of the toroid, the values of $\beta^{\pm}$ and β^0 were obtained where β^0 is the propagation factor when the magnetization is set to zero. The results are shown in Fig. 4. The values of (βb), and $(\beta^+ - \beta^-)b$ (differential phase shift) are given in radians (to convert these into degrees/inch-GHz, they have to be multiplied by a factor of 26.95).

The results show, as expected, that the differential phase shift passes through a maximum when the inner toroid is placed there where the magnetic field was circularly polarized in the absence of both toroids. Thus, to find the inner toroid location which maximizes the differential phase shift, it is sufficient to solve the much simpler problem. As expected, the differential phase shift is increased by a factor of about 2 with respect to the single-toroid geometry.

The next step is to repeat the calculations when the inner toroid is fixed and the outer toroid's position is changed around the previously used value while all the other parameters remain unchanged.

For $r_1/\lambda_0 = 0.0351$, the results are given in Fig. 5. The differential phase shift increases as the outer toroid is brought closer to the dielectric loading cylinder, and the increase can be considerable. Also note that it depends almost linearly on the location of the outer toroid. Thus, to obtain maximum differential phase shift, the ratio r_2/r_1 has to be small, and a compromise has to be adopted if the biasing method is based on the $1/r$ dependence of the applied H_{dc} field.

The next step was a computation using as a variable the thickness of the toroids. The location of the inner toroid is left unchanged and the outer toroid is placed at $r_2/\lambda_0 = 0.108$, a value chosen such that the ratio r_2/r_1 is sufficiently large. As the thickness is increased, so is b_1, in order to offset the elimination of the high dielectric constant loading material.

The results appear in Fig. 6. Again, the differential phase shift increases as the toroid thickness increases; but an increase in toroid thickness brings about a deterioration of the squareness of the hysteresis loop of the ferrite material and also a reduction of window bandwidth, since more material with a relatively low dielectric constant is introduced into the guide. Note, however, that the rate of increase of the differential phase shift decreases substantially for $\delta/\lambda_0 = 0.02$ (twice the original value) and the other parameters are left unchanged. The differential phase shift increases almost linearly as the remanent magnetization is increased, as is the case for the twin-slab rectangular geometry (Fig. 7).

It is considerably more complicated to obtain a theoretical calculation of the losses incurred by this configuration. Consequently, the calculation of the figure of merit (differential phase shift/loss) has not been completed. But, as pointed out by Ince and Tsandoulas [2], the TE_{01} mode has inherently small losses, and since the RF fields

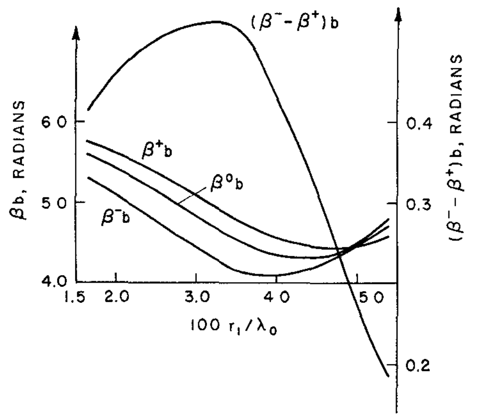

Fig. 4. Normalized propagation factors and differential phase shift versus normalized position of inner toroid.

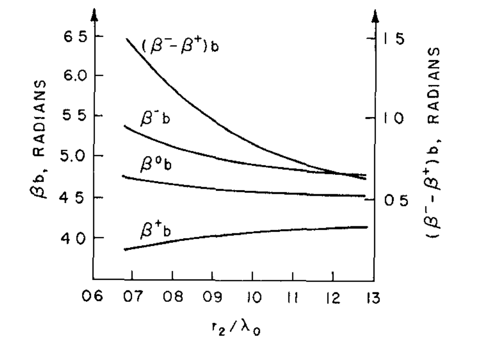

Fig. 5. Normalized propagation factors and differential phase shift versus position of outer toroid.

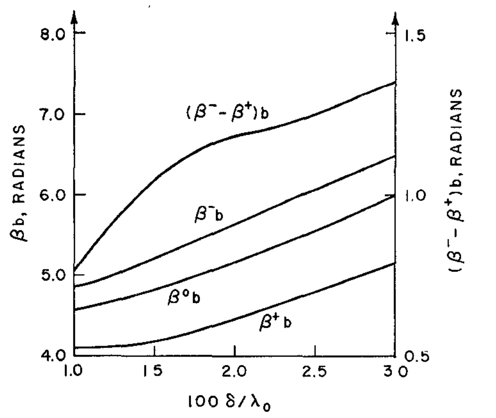

Fig. 6. Normalized propagation factors and differential phase shift versus normalized toroid thickness.

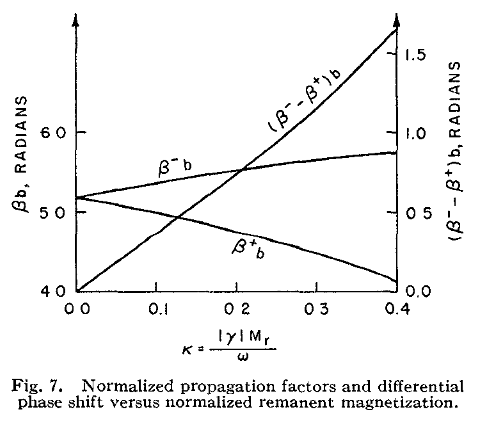

Fig. 7. Normalized propagation factors and differential phase shift versus normalized remanent magnetization.

are not appreciably distorted from those for the isotropic case, these cannot be expected to increase above the loss introduced by the ferrite toroids.

Although all these computations have been performed for particular values and limited ranges of the different parameters involved, it is clear that the form of the variation of the differential phase shift with these parameters will not depend on the particular values chosen. In particular, the almost linear dependence with respect to remanent magnetization and outer toroid location can be used to scale any given value of the differential phase shift for any other values of these parameters. The location of the inner toroid is more critical, but this can be predicted quite accurately by obtaining the lesser of the two loci where the magnetic field is circularly polarized.

Conclusions

For ferrite loaded devices such nonreciprocal parameters as differential phase shift may well prove maximal for the twin-ferrite-toroid loaded waveguide operating in the TE_{01} mode where the toroids can be magnetized at remanence in opposite direction by means of a single axial wire. The differential phase shift is maximized when the inner toroid is positioned near that point where the magnetic field intensity for the unloaded guide is circularly polarized, but this does not hold for the outer toroid. Also the differential phase shift increases almost linearly with increasing normalized remanent magnetization.

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A Reference Noise Standard for Millimeter Waves

W. C. DAYWITT

***Abstract*—The WR15 thermal noise standard that is used as the national reference standard of noise power in the frequency range from 56 to 64 GHz is described in this short paper. The source forms a basis for both the noise-power comparison service and noise-figure service offered by the National Bureau of Standards in this frequency range.**

Introduction

The Electromagnetics Division of the Institute for Basic Standards of the National Bureau of Standards (NBS) offers calibration services of effective noise power emerging from a noise generator.

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