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New Uniaxial-Ferrite Millimeter-Wave Junction Circulators*

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ABSTRACT

Progress is reported in the development of millimeter-wave microstrip and waveguide junction circulators for the band near 31 GHz. By exploiting the properties of high-anisotropy magnetic materials, external magnet requirements are eliminated. Favorable isolation and insertion loss performance, with good temperature stability, are achieved. Design tradoffs involve device structure and magnetic material parameters.

1. INTRODUCTION

We report on progress in the development of millimeterwave junction circulators for the band near 31 GHz, incorporating the technique [1,2,3] of exploiting the high effective internal magnetic anisotropy field of barium and strontium magnetoplumbites (hexagonal ferrites) to eliminate the external permanent magnet requirement. Microstrip and waveguide three-port junction versions have been built and evaluated, exhibiting good isolation and insertion loss performance, and requiring no magnet. Design considerations include the magnetic material parameters: remanent magnetization, anisotropy, coercive field, resistivity, and shape-dependent demagnetizing effects; also, microstrip and waveguide junction circuit geometries, dissipative effects, temperature stability, and influences of coax-microstrip transducers.

2. FREQUENCY-SCALING PROBLEMS

It is a well-known vexation in millimeter-wave system design that, with increasing frequency, nonreciprocal devices which depend on the gyromagnetic properties of the iron-oxide materials – the ferrimagnetic spinels and garnets – become more difficult to design and fabricate, and performance becomes progressively degraded. Beyond the general problem of increasing losses, the underlying Larmor magnetic resonance relation $\nu = \gamma H$ which calls for an applied d.c. magnetic field H proportional to frequency ν, leads to requirements for inconveniently large magnets. Furthermore, the strength of the electromagnetic interaction, governed by the ferrite saturation-magnetization value which is physically limited to values less than about 5000 gauss, begins to weaken appreciably at frequencies above 20 GHz. Some ingenious efforts have been reported [4] on designs that utilize so-called low-field nonreciprocal effects in longitudinally magnetized ferrites for millimeter-wave use. Present technology, however, relies principally on adaptation of successful designs from the 1-18 GHz range, which are subject to various difficulties including those indicated above that interfere with the effort to scale to higher frequencies.

3. PERMANENT MAGNET MATERIALS

The Kittel magnetic resonance equation [1,5,6] (see Sec. 4), formulated to incorporate the influences of both dipolar and magnetocrystalline anisotropy interactions, suggests strategies by which the effective anisotropy field and shape-dependent demagnetizing field might be adapted so as to compensate for the limited magnetization. Designs exploiting anisotropy as a magnetic bias effect are known in the ferrite device art [2,7]. With the availability of high-quality magnetically hard (permanent-magnet) materials, the possibility has emerged that the required magnetic state can be created internally, avoiding altogether the need for an external magnet. The advantages, principally reductions in weight, volume, and structural complexity, would be highly significant in many important applications. With anisotropy fields approaching 20 kOe (corresponding to frequencies exceeding 50 GHz) such materials are potentially capable of conferring very useful millimeter-wave performance, provided they can be made to remain in a stable magnetized state (primarily determined by coercivity and demagnetizing effects). Permanent-magnet sintered uniaxial magnetoplumbites with suitable crystallite structure and orientation are commercially available. We have undertaken

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to determine whether this class of materials can offer acceptable magnetic characteristics together with favorable microwave properties.

Since dielectric properties of ferrites in general are of major concern in any micowave application, the adaptation of commercial permanent-magnet materials to a millimeter-wave device must be approached with caution. The presence of small quantities of ferrous iron impurities in the chemical formula can cause unacceptable losses. For this reason, any serious development efforts in this direction must include capability of characterizing the material specifically in this respect, since loss determination through device performance alone normally yields a combination of magnetic and dielectric absorption, further obscured by the normal mismatch effects associated with the device structure. Our results to date, to be presented, have shown no serious indication of dielectric loss effects.

4. PERMANENT-MAGNET FERRITE DESIGN FOR A JUNCTION CIRCULATOR

Assuming cylindrical ferrite symmetry, the field-frequency relation for magnetic resonance is [6]

$$\frac{\nu}{\gamma} = H_0 + H_A + (N_t - N_z)M$$

where ν is frequency, γ is the gyromagnetic ratio $\gamma = 2.80 \times 10^6$ Hz Oe^{-1}; H_0, H_A are respectively the applied d.c. magnetic field and the internal magnetocrystalline anisotropy field, $4\pi M$ is the magnetization, and N_t, N_z are respectively the transverse and longitudinal factors that determine the internal demagnetizing field. H_A is directed parallel to M so that, for a permanent-magnet material in its remanent state with $H_0 = 0$, the resonance frequency is determined by the anisotropy field, modified by the demagnetizing field. In waveguide junctions the ferrite may be in the form of a cylinder, with the ratio of axial length to diameter adjustable within the constraints imposed by the circulation conditions. Thus, for a given H_A there is an option to select the shape (hence the value of $N_t - N_z$) so as to adjust the effective field to meet an operating frequency requirement. If the coercive field H_c of the material is less than the saturation magnetization $4\pi M_s$, the demagnetizing effect may have to be reduced in order to maintain a strong, stable state of remanent magnetization. In microstrip junctions the ferrite element has customarily been made in the form of a thin disc, which has unfavorable demagnetizing factors ($N_z \cong 4\pi$, $N_t \ll N_z$). A solution may be to substitute a material of higher coercivity, provided it fulfills the conditions for favorable microwave performance – principally low dissipation. An alternative is to adopt a "thick-disc" geometry which confers the same adjustability of the demagnetizing effect as in the waveguide structure, provided excitation and coupling of such a ferrite element can be accomplished in a primarily planar circuit structure.

Depending on the particular application and its environment, the temperature sensitivities of the various terms in the resonance condition, Eq. (1), can be of critical importance in microwave devices. According to the data for barium ferrite [8] shown in Fig. 1, $4\pi M_s$ and H_A have compensating trends with temperature changes up to 500 K. As expected, the magnetization decreases with increase of temperature toward a Curie point of approximately 700 K. Contrary to conventional (isotropic) ferrites, however, for which H_A also decreases, in the barium ferrites the slope has the opposite sign over the range of interest, namely 250 to 350 K. By inspection of Eq. (1) one can see how the geometrical demagnetizing factors may be selected to confer a temperature-insensitivity of resonance frequency.

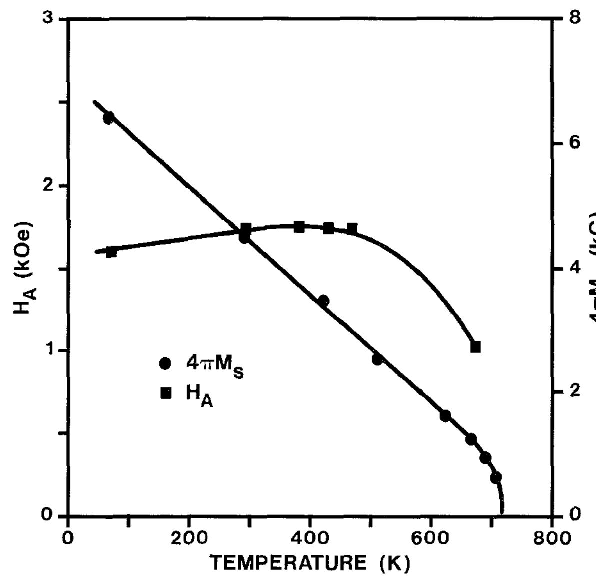

Fig. 1. Anisotropy field and saturation magnetization of barium ferrite as functions of temperature [8].

5. RECTANGULAR-WAVEGUIDE THREE-PORT JUNCTION CIRCULATOR

Basic theory and principles of operation of microwave junction circulators of the distributed type were presented by Bosma [9] and by Fay and Comstock [10]. A millimeter-wave design requiring no magnet was successfully demonstrated by Akaiwa and Okazaki [2]. The EHF-band three-port waveguide circulator design of Piotrowski and Raue [11] was adapted for our work, principally by substitution of the oriented polycrystalline strontium ferrite uniaxial material $SrFe_{12}O_{19}$ in place of the nickel ferrite reported by them. The remanent magnetization $4\pi M_r$ is 4000 gauss, and the coercive field H_c is approximately 600 Oe (a rather low value which was accepted because this material offered exceptionally high resistivity, hence favorably low dielectric loss). The device is shown in Fig. 2. The ferrite elements, two cylinders of diameter 0.060 in. and axial length 0.060 in., were magnetized to saturation and removed from the magnet in a stable remanent state. The data of Fig. 3 are the forward loss and isolation for the three pairs of ports, showing isolation greater than 26 dB centered at 30.7 GHz; greater than 20 dB over a band of about 1%. Insertion loss is less than 1 dB. Fig. 4 shows the performance at four temperatures from −20 to +50 °C, indicating quite stable performance above about 0 °C.

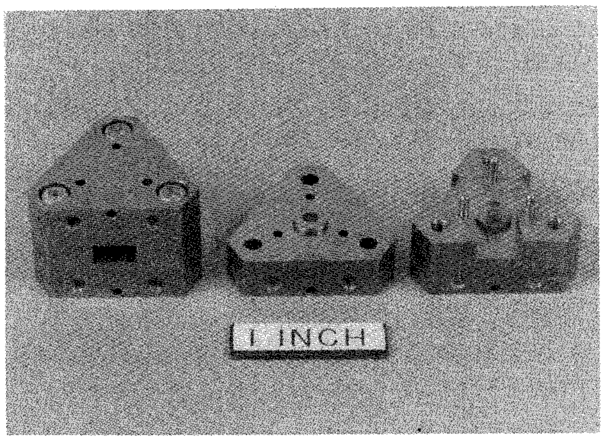

Fig. 2. The 31-GHz waveguide circulator; assembled, and opened to show junction details.

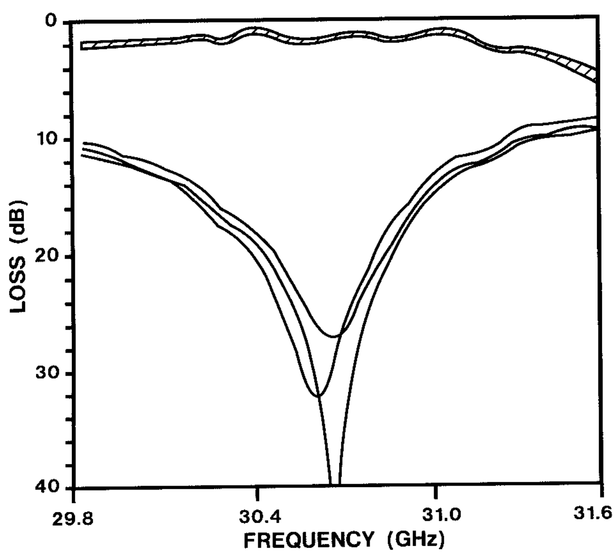

Fig. 3. The waveguide circulator: insertion loss and isolation measured at the three ports.

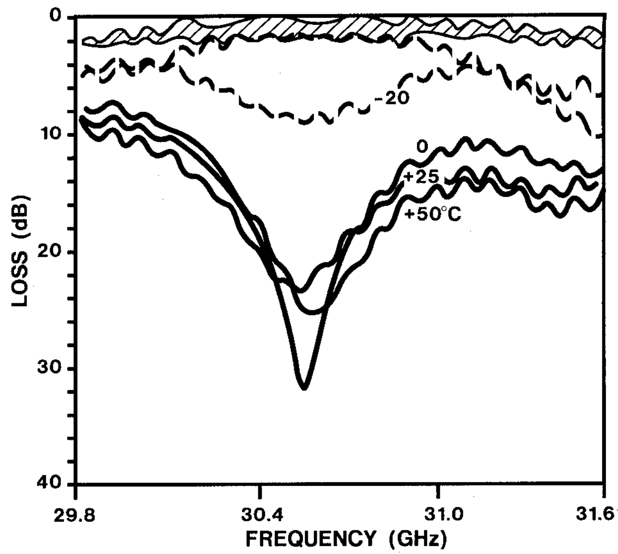

Fig. 4. The waveguide circulator: temperature dependence of insertion loss and isolation. $T = -20$, 0, +25, and + 50 °C.

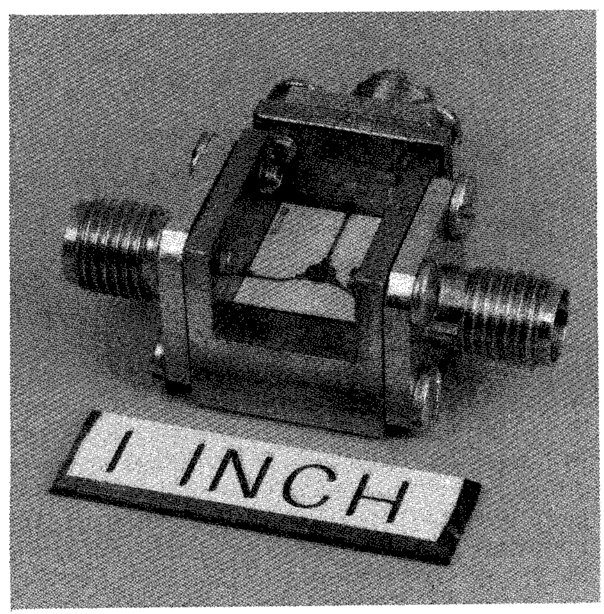

Fig. 5. The 31-GHz microstrip circulator. The uniaxial ferrite cylinder is located below the metal junction overlay.

6. MICROSTRIP JUNCTION CIRCULATOR

The planar form of the microstrip circulator was modified in order to accomodate the material of somewhat low coercive field cited in Sec. 5. The device is shown in Fig. 5. The circuit substrate is 0.010 in. thick with a hole of 0.060 in. diameter at the junction; the hole was continued 0.050 in. deep into the fixture ground plane to provide a socket for a single ferrite cylinder 0.060 in. long. The insertion loss and isolation are shown in Fig. 6: insertion loss less than 2 dB over a band of 5% centered at 30.8 GHz and isolation greater than 20 dB over that band.

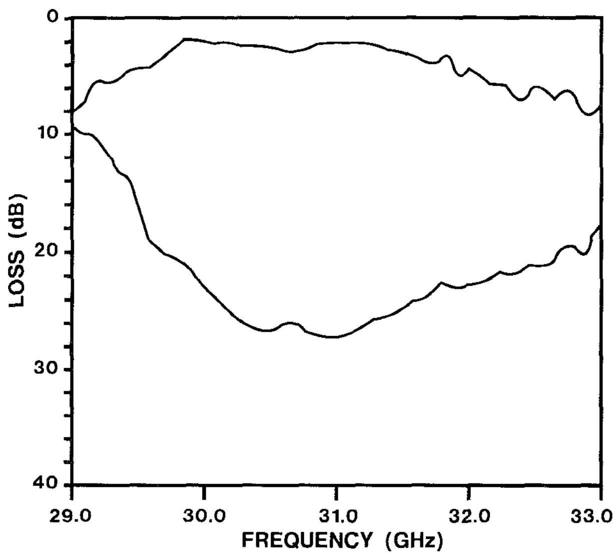

Fig. 6. The microstrip circulator: isolation and insertion loss.

7. CONCLUSIONS

With the results reported here on waveguide and microstrip circulators we have confirmed the feasibility of the design principle and demonstrated its application in both waveguide and microstrip embodiments: namely, to exploit the high magnetocrystalline anisotropy and consequent high-coercivity behavior of suitable magnetoplumbite materials to obtain circulator action without the need for an external magnet in the device structure. Further detailed studies of the magnetic parameters and their relation to device structure and performance are now contemplated.

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