QUASI-OPTICAL FERRITE ROTATOR FOR MILLIMETER WAVES

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ABSTRACT

A nonreciprocal 45-degree Faraday rotator has been developed for use in optical beams at 35 GHz. In laboratory demonstrations, an effective isolation greater than 40 dB and an insertion loss considerably less than 0.1 dB over a frequency band from 32 to 39 GHz (~ 20 %) have been measured.

1. INTRODUCTION

The phenomenon of gyromagnetic Faraday rotation has found important uses in a variety of microwave control applications [1]. With waveguide structures, the magnetized ferrite required for the gyromagnetic effect is placed inside the guide; in configurations more appropriate for two-conductor lines, such as stripline or microstrip, the ferrite has a planar geometry with metallized patterns on the surfaces to define the circuit function. For the conventional microwave region (10 to 1 cm wavelength), dimensional constraints do not usually impose difficulties in component design and fabrication. At millimeter wavelengths (below 1 cm), however, several problems begin to appear. Since waveguide dimensions and tolerances become more critical, the ferrite must also be carefully machined, and the ceramic quality must accordingly meet higher standards. In addition, ohmic losses in both waveguide and planar structures increase with frequency, and the corresponding ferrite components become less efficient because of magnetic material limitations that become significant above 35 GHz. For waveguide applications in particular, further difficulties can arise from heat dissipation requirements and arcing caused by high electric fields in confined spaces.

As a consequence, optical techniques offer attractive alternatives to waveguide and planar devices where space and weight limitations are sufficiently generous to permit transmission of Gaussian beams fashioned and controlled by quasi-optical components [2], [3]. What has been absent in this emerging technology, however, are optical analogs to the nonreciprocal Faraday rotation devices so important in conventional microwave systems.

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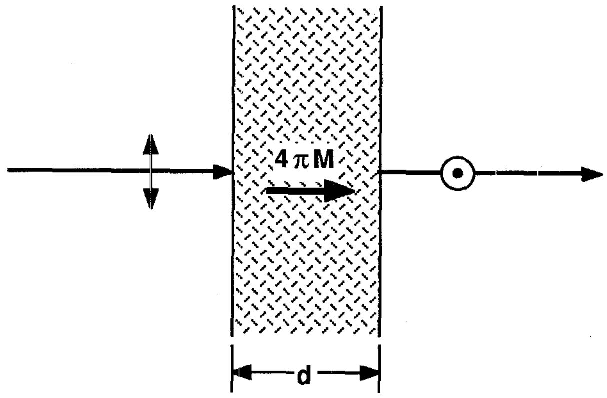


Fig. 1. 90-degree Faraday rotation of a linearly polarized plane wave traversing a semi-infinite magnetized medium.

2. GYROMAGNETIC FARADAY ROTATION

For the linearly polarized plane wave traversing a semi-infinite medium of magnetization $4\pi M$ and uniform thickness d shown in Fig. 1, the principles of ferrimagnetic resonance (FMR) apply where the magnetization is collinear with the direction of propagation. Since the propagation constants of the two counterrotating circularly polarized components of the beam are influenced differently according to the dispersion of the magnetic permeability, the individual phase angles in radians may be expressed as [4]

$$\varphi_{\pm} = \beta_{\pm} d = (2\pi\omega/c)(\varepsilon_f \mu_{\pm})^{1/2} d \quad , \qquad (1)$$

where $\beta_{\pm}$ is the propagation constant, $\mu_{\pm}$ the permeability, ω the frequency in Hz, ε_f the dielectric constant, and c the velocity of light. With the appropriate relations for $\mu_{\pm}$ in Eq. (1), the rotation angle $\theta = (1/2)(\varphi_- - \varphi_+)$ becomes

$$\theta = (2\pi\omega/2c)\varepsilon_f^{1/2} d\{[1+\gamma 4\pi M/(\omega_0+\omega)]^{1/2} - [1+\gamma 4\pi M/(\omega_0-\omega)]^{1/2}\} \quad , \qquad (2)$$

where γ is the gyromagnetic constant (= 2.8×10^6 Hz/Oe) and ω_0 is the FMR frequency. If $\omega_0 << \omega$ (the "below resonance" condition) and $\gamma 4\pi M < \omega$, Eq. (2) reduces to the frequency-independent approximation

$$\theta \approx (2\pi\varepsilon^{1/2}/2c)(\gamma 4\pi M)d \quad . \qquad (3)$$

The critical design parameter for a Faraday rotator is therefore the $(4\pi M)d$ product. For a 45-degree rotation of a 35-GHz beam from a single pass through a ferrite with $\varepsilon_f = 14.5$, the relation of Eq. (3) between $4\pi M$ and d is plotted in Fig. 2. The advantage of using high-magnetization material to minimize signal absorption by reducing thickness is readily apparent.

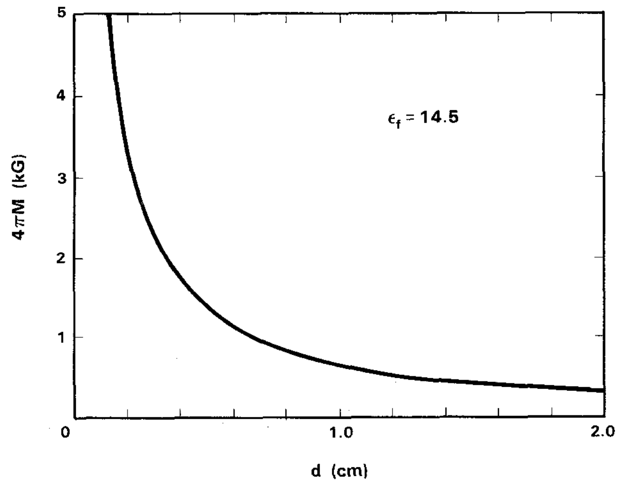


Fig. 2. Design tradeoff between $4\pi M$ and d for $\varepsilon_f = 14.5$, based on Eq. (3).

3. ROTATOR DESIGN

To adapt the above theory to a practical rotation device, a ferrite medium magnetized along its axis is required; in addition, impedance matching is necessary to eliminate reflections at entrance and exit surfaces. As a result, the rotator takes the form of a ferrite disk sandwiched between quarter-wave plates (of thickness equal to an odd multiple of a quarter wavelength) with a dielectric constant ε_d that satisfies the antireflection condition,

$$\varepsilon_d \approx (\varepsilon_a \varepsilon_f)^{1/2} \quad , \qquad (4)$$

where the third dielectric medium is air with $\varepsilon_a = 1$ and the permeability of the ferrite is near unity far from resonance.

Since the ferrite cannot readily be part of a closed magnetic circuit in this configuration, its shape demagnetizing field (~ $4\pi M$ in the case of a thin disk) must be overcome by an external magnetic field, according to

$$H \geq 4\pi M - H_c \quad , \qquad (5)$$

where H_c is the coercive field. For this application, magnetically *soft* garnets with small H_c values (~ 1 Oe) were chosen because of their narrow FMR linewidths and superior dielectric properties. An additional benefit from this class of materials is the compatibility [through Eq. (4)] of the dielectric constant with that of quartz ($\varepsilon_d \approx 3.8$) , which may conveniently serve as the material for antireflection plates.

The approximate physical dimensions are indicated on the sketch in Fig. 3. Thickness of the ferrite, of course, is dictated by the $4\pi M$ value, as determined from the curve in Fig. 2. Since surface finish requirements are not critical at these wavelengths, polishing was not found to be necessary for this application. Interface flatness, however, was maintained to within a tolerance of ± 0.01 in. In this prototype rotator, the external field was provided by a pair of electromagnets arranged in the manner of Fig. 4.

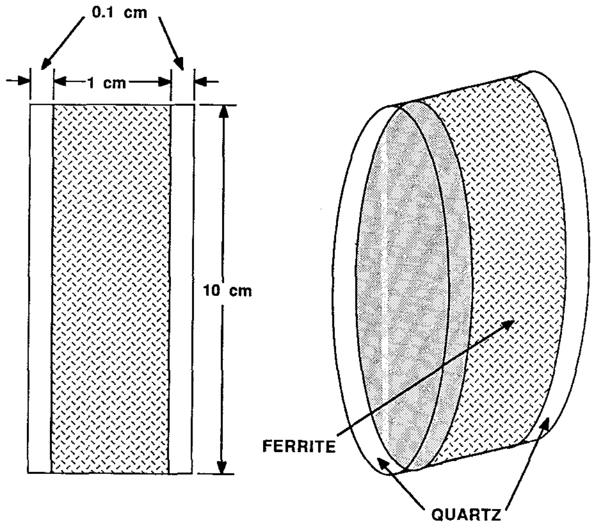


Fig. 3. Ferrite rotation element sandwiched between two quartz antireflection plates.

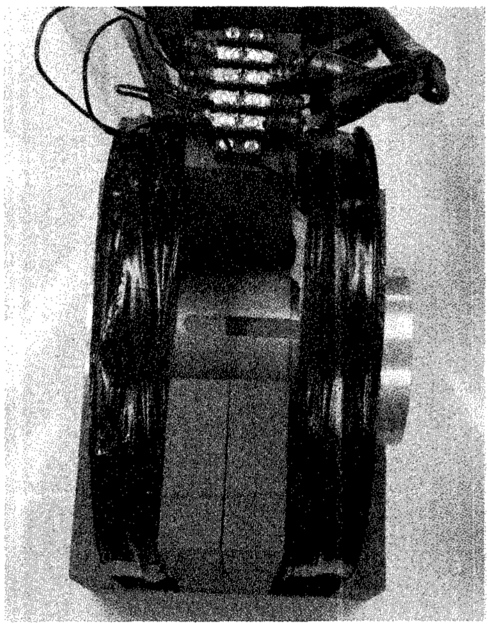


Fig. 4. Photograph of experimental Faraday rotator, with a pair of coils coaxial with the element.

With the introduction of a 3-dB polarizing beamsplitter in the form of a wire grid [5], [6], the rotator can be an isolator or three-port circulator, as explained in Fig. 5. A wave with vertical polarization at port 1 traverses the beamsplitter (oriented to be transparent), undergoes a 45-degree clockwise rotation, and arrives at port 2. An ideal reflection preserves the polarization and the rotation angle will be doubled to 90 degrees on the return pass because of the nonreciprocal property of the ferrite. An encounter with the beamsplitter by the now horizontally polarized return wave will cause a reflection into port 3.

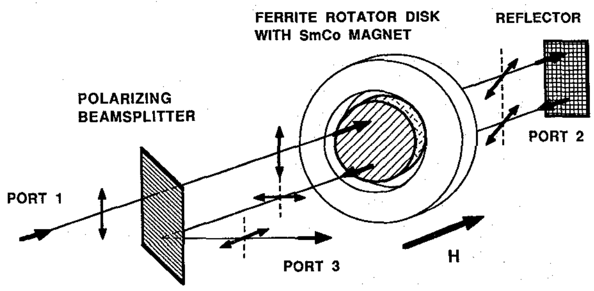


Fig. 5. Diagram of a three-port circulator with SmCo permanent magnet, indicating polarization directions and the function of the wire grid.

4. EXPERIMENT AND RESULTS

In order to create an optical beam suitable for the rotator, the signal was first transmitted through dominant-mode rectangular waveguide from a K_a-band sweep generator, and then converted to a space wave with a Gaussian intensity profile by means of a corrugated horn and computer-contoured reflectors, as shown schematically in Fig. 6 and as a photograph in Fig. 7. The rotator was inserted at the beam waist and the rotated polarization was analysed by a second reflector/horn combination, with the detected signal fed to a network analyser. To measure the rotation angle and insertion loss, the receive horn (with its polarization axis defined by the attached rectangular waveguide) was rotated to maximize the detected signal; the insertion loss was simply the differnce in level with and without the rotator in place. The effective isolation (set by the amount of elliptical polarization created by the passage through the ferrite) was determined from the reduction in signal strength with the receive horn axis at 90 degrees to the rotation angle.

Over a band from 32 to 39 GHz, corresponding to a 20 % bandwidth, numerous tests were carried out to establish the gyromagnetic properties of this device. With near-optimum matching of the antireflection plates to a 1000-G YAlFe garnet, the signal after a 45-degree rotation is compared with the reference (no rotator) in Fig. 8. As indicated by the scope trace, the small insertion loss is difficult to discern in the presence of standing waves caused by residual reflections among components of the beam system. With the 0.2 dB/cm scale, the absorption appears to be ~ 10^{-2} dB, which is consistent with the dielectric loss tangent of ~ 10^{-4} for this garnet family. With the receive horn set at 90 degrees to the rotated polarization, the detected signal decreased by more than 40 dB. As a result, it was concluded that the cross-polarized component was negligible in this configuration.

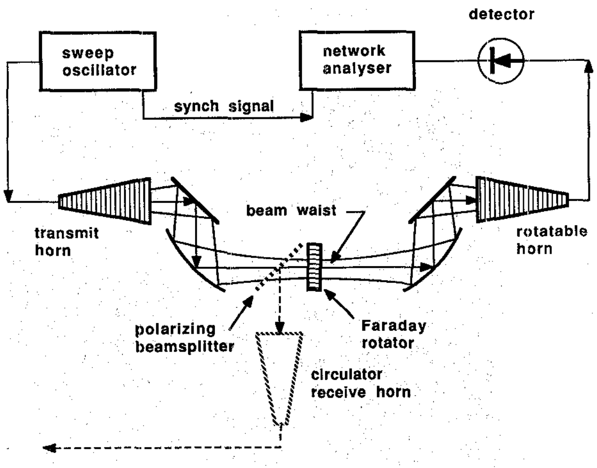


Fig. 6. 35-GHz quasi-optical measurement system.

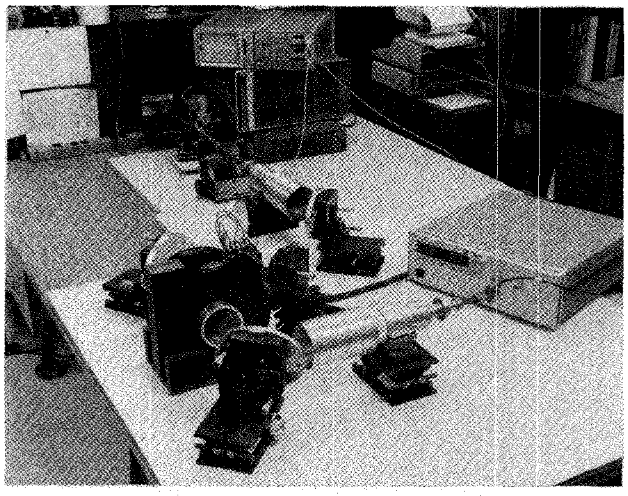
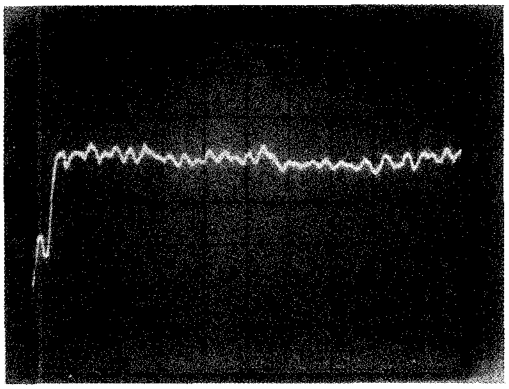


Fig. 7. Photograph of measurement system.

5. CONCLUSIONS

Quasi-optical devices for nonreciprocal applications at millimeter wavelengths are not only feasible, but offer distinct advantages over more conventional geometries. Where space permits, both power consumption and power-handling capability may be superior. In addition, component complexities and fabrication costs should be reduced. Since signal attenuation will be minimized by maintaining the smallest ferrite thickness, practical frequency limitations will ultimately be determined by the maximum available $4\pi M$ (~ 5000 G) of the ferrite (see Fig. 2). For a disk geometry, the magnet structure required to saturate the rotation element will also become larger. However, since physical dimensions will scale down with decreasing wavelength, nonreciprocal optical-beam control devices should become a reality for frequencies above the 95 GHz of devices currently under development.

WITHOUT ROTATOR



WITH ROTATOR

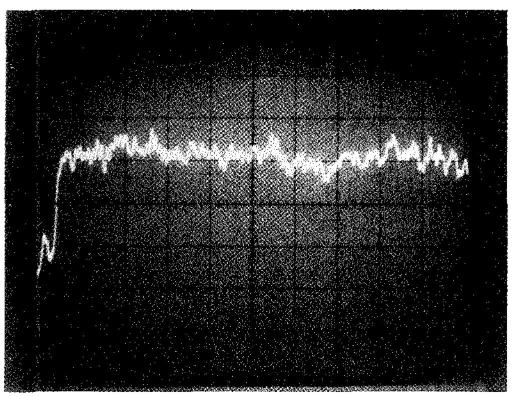


Fig. 8. 45-Degree rotated signal from 32 to 39 GHz, indicating negligible insertion loss.

ACKNOWLEDGMENT

The authors are grateful to James F. Fitzgerald and Dennis R. LaFosse for fabrication, assembly, and testing related to the work reported in this paper.

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