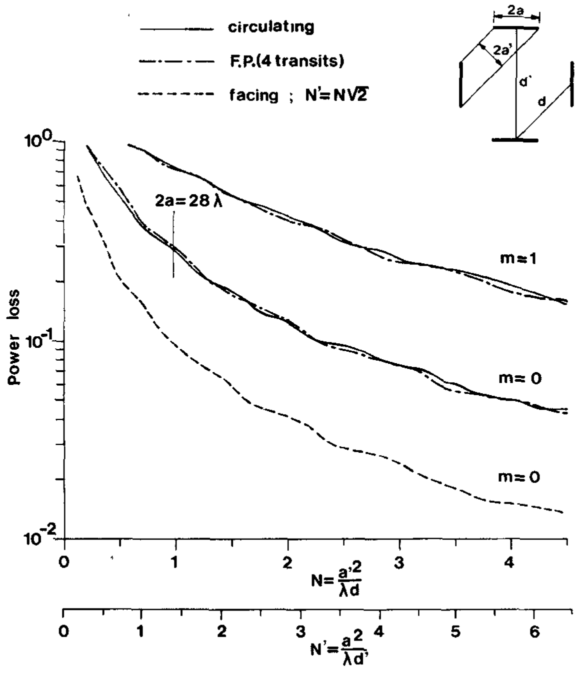

Fig. 3. Computed power loss per round trip for first even and odd modes versus $N = a'^2/\lambda d$, compared with the four-transit power loss of the equivalent Fabry–Perot. Dotted line refers to facing mode loss versus $N' = a^2/\lambda d'$.

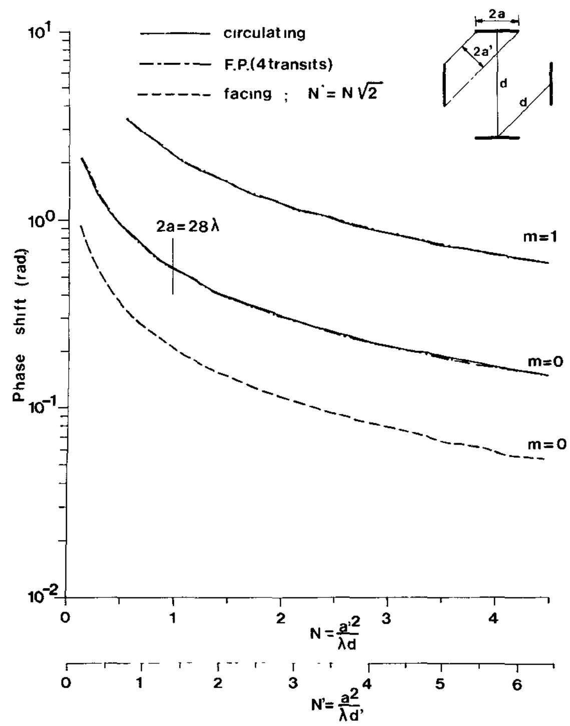

Fig. 4. Computed phase shift per round trip for first even and odd modes versus $N = a'^2/\lambda d$, compared with the four-transit phase shift of the equivalent Fabry–Perot. Dotted line refers to facing mode phase shift versus $N' = a^2/\lambda d'$.

equation for different resonator sizes, taking an input function with a constant phase-front normal to the line joining the centers of two consecutive mirrors.

The computations were limited to the first even and odd modes. The power losses per round trip for such circulating modes are shown in Fig. 3 (continuous lines) plotted versus Fresnel number $N = a'^2/\lambda d$ with $2a'$ being the actual aperture of the mirror projected in the beam direction ($2a' = 2a \cos \pi/4$). The dotted–dashed lines correspond to the losses per four transits of a Fabry–Perot having mirror aperture $2a'$ and spacing d equal to the distance between the centers of two adjacent mirrors.

The lower dashed curve represents the losses of the "facing zeroth-order mode" plotted versus Fresnel number $N' = a^2/\lambda d'$ with $d' = d/(\cos \pi/4)$. The Fresnel number N' is obtained from N, $N' = N\sqrt{2}$. Accordingly, the facing mode losses are always lower than those of the circulating mode. The presence of one or the other type of modes does not only depend on the assumed excitation, because the diffracted energy of the circulating mode will always excite the facing mode, and as the iteration process is continued, only the mode normal to the mirrors remains. Hence, below a given mirror size, the steady-state circulating solution can be obtained only by inhibiting the contribution of the facing mirror, which physically is equivalent to blocking the direct path through the center of the ring resonator. In our case this occurred for about $2a = 28\lambda$ ($2a' = 20\lambda$).

Fig. 4 shows the phase shifts of the modes plotted versus N and N', respectively.

The zeroth-order mode pattern has a configuration across the beam of the type of the zeroth-order mode of the planar Fabry–Perot resonator and a similar configuration across the mirror, but with a slight asymmetry depending on the assumed circulation sense. It is to be noted that when considering the first odd mode, due to the tilting of the mirrors with respect to the circulating mode wavefront, although using an odd input function, a mode conversion occurs that gives rise, after a certain number of iterations, to the even lowest order mode. Consequently, a method [6] has been applied which substantially consists of eliminating at each iteration the component of the zeroth mode by the use of the orthogonality of the solutions. Another anomalous behavior of such mode is that for each value of N, according to the chosen combination mirror aperture/spacing, it is possible to find a mode having the same loss and phase shift as the odd mode but a completely different field configuration.

In conclusion, these results show that in a four flat-mirror ring resonator two sets of modes exist: circulating and facing modes, both essentially of the planar Fabry–Perot type. Facing modes always have lower losses, and in some cases the diffracted energy is so high that only the facing mode is excited.

The losses of the circulating modes can be evaluated on the basis of the losses per four transits in the equivalent Fabry–Perot resonator.

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Dissipative Parameters in Ferrites and Insertion Losses in Stripline *Y* Circulators below Resonance

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Abstract—**Extensive microwave loss measurements have been performed at the frequency of 1.3 GHz on below resonance stripline *Y* circulators loaded with aluminum doped YIG. External χ'' have been measured on the same compositions. Also, dielectric loss**

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measurements have been carried out. A relation is found which correlates insertion loss in stripline circulators with loss parameters χ'' and tan δ.

The relationship between the ferrite parameters and insertion losses (IL's) in the waveguide Y circulators was thoroughly discussed in a previous paper [1]. In [1] extensive microwave loss measurements were shown from 1.3 to 11 GHz on below resonance waveguide Y circulators loaded with a wide variety of ferrite and garnet compositions.

Dissipative internal and external magnetic parameters were measured on the same compositions. Also, dielectric loss measurements were carried out. It was inferred that the IL of such devices is independent of ΔH and mainly depends on the internal dissipative susceptibility and on the dielectric loss tan δ.

The relation of the IL versus χ'' and tan δ in the case $\omega_m/\omega \leq 0.8$ was found independent of frequency and given by the semiempirical equation

$$\mathrm{IL} = 10 \log_{10} (1 - 2.85\chi'' - 1.60 \tan \delta - 0.017)^{-1}. \quad (1)$$

We have recently performed a similar investigation on the relationship between ferrite parameters and IL in a different geometry, that is on stripline circulators magnetized below resonance.

The results obtained with this new geometry, confirm the opinion—expressed in the conclusions of [1]—that the IL on below resonance circulators is not critically influenced by the specific geometry involved, but it is essentially dominated by the dissipative parameters of the ferrite. Measurements were performed on a device having geometries as in Bosma [2] and in Fay–Comstock [3]. Experimental results have been carried out on ten samples of aluminum doped garnets having χ'' and tan δ as in Table I. IL and χ'' were both measured at the frequency of 1315 MHz. IL was measured on a circulator mounted with the two ferrite disks having the same χ''.

Special attention was exercised in keeping the VSWR level below 1.1. χ'' was measured on the same disks in a waveguide TE_{102} cavity. Tan δ and ϵ are measured on small rods (1 mm diam and 15 mm long), in the center of a rectangular TE_{103} cavity at 9.4 GHz. These samples were obtained from the same measured disks.

The measurements of $4\pi M_s$, ΔH, and g were made on small spheres (ΔH and g at 9.5-GHz frequency). Measurements precision was assessed to be ± 10 percent. The two χ'' values reported in Table I refer to the two disks used in each circulator.

The procedure applied in [1] leads—for the IL—to an expression of the following type [1, eq. 15]:

$$\mathrm{IL} = 10 \log_{10} (1 - A\chi'' - B \tan \delta - C)^{-1}. \quad (2)$$

As we shall see later, in our case the term $B \tan \delta$ can be suppressed. Utilizing (2) and looking for the best fitting through the experimental points, we determine the values of A and C and obtain the following expression:

$$\mathrm{IL} = 10 \log_{10} (1 - 3.08\chi'' - 0.022)^{-1}. \quad (3)$$

The results are shown in Fig. 1.

As the equivalent circuit of the circulator is a parallel resonant circuit, the IL is

$$\mathrm{IL} = 10 \log_{10} \left(1 - \frac{Q_L}{Q_0}\right) \quad (4)$$

where Q_L is the loaded Q, Q_0 unloaded Q, and Q_0 and Q_L are given by the expressions (see [3])

$$\frac{1}{Q_0} = \tan \delta + \frac{\mu_e''}{\mu_e'}$$

$$Q_L = \left(\frac{\omega_0}{\omega^+ - \omega^-}\right)\frac{1}{\sqrt{3}}. \quad (5)$$

In our case ($\mu_e' \simeq 1$, μ_e'', and $k'' \ll 1$ see [1]) we have

$$\mu_{\mathrm{eff}} = \frac{(\mu' - j\mu'')^2 - (k' - jk'')^2}{\mu' - j\mu''} \simeq 1 - k'^2 - j\mu''(1 - k'^2) \quad (6)$$

where $k' = \gamma 4\pi M_s/\omega$.

TABLE I

DIELECTRIC AND MAGNETIC PROPERTIES OF THE FERRITE USED IN THE CIRCULATORS OF FIG. 1

Circulator	$4\pi M_s$ (G)	ΔH (Oe)	g	ε	$\tan\delta \cdot 10^3$	$\chi'' \cdot 10^3$
1	400	50	2,00	14,2	2,4	13 15
2	360	85	2,00	14,8	0,8	13 15
3	400	40	2,00	15,5	1,8	13 15
4	400	50	2,00	14,2	2,4	16 16
5	400	50	2,00	14,2	2,4	16 17
6	400	50	2,00	14,2	2,4	16 17
7	400	40	2,00	15,5	1,8	22 21
8	400	40	2,00	15,5	1,8	23 23
9	400	40	2,00	14,7	2,1	28 28
10	400	40	2,00	14,7	2,1	28 29

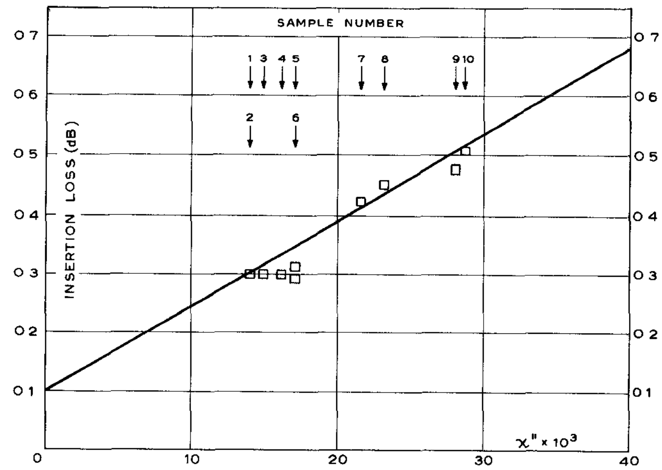

Fig. 1. Circulator insertion loss as a function of χ_e''.

Equation (6) allows us to determine IL:

$$\mathrm{IL} = 10 \log_{10} \left\{1 - Q_L\left(\tan \delta + \frac{1 + k'^2}{1 - k'^2}\chi''\right) - C\right\}^{-1}. \quad (7)$$

Because of the nonhomogeneous magnetic field inside the disks of the ferrite we suppose that $4\pi Ms$ is likely to vary between 300 and 400 G and so we have

$$Q_L \frac{1 + k'^2}{1 - k'^2} = 2.3 \div 4.2. \quad (8)$$

As we can see, the range defined for the term A by (8) is in good agreement with the experimental value furnished by (3). Besides, the term A, *a priori* dependent on the geometry involved, see [1], is approximately the same in (1) and (3). So the experimental results again demonstrate that the IL of a circulator mainly depends on the loss properties of the ferrite.

In a specific case, such losses are essentially expressed by χ'', as the dielectric losses, represented by the term $B \tan \delta$, do not contribute as we can see on the basis of experimental results (Fig. 1) and theoretical consideration (7).

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Low-Loss Two-Dimensional GaAs Epitaxial Waveguides at 10.6-μm Wavelength

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Abstract—**The successful fabrication of low-loss two-dimensional GaAs epitaxial waveguides by chemical etching for use in integrated optics at 10.6 μm is reported. Selective excitation of specific E_{pq}^y modes was observed by placing the prism at specific angles in the horizontal plane. Loss measurements showed no increase in attenuation for lower order E_{pq}^y modes (as compared to corresponding one-dimensional waveguide modes) when the guide width is 50 μm. As the guide width is reduced, there is a significant increase in attenuation as p increases.**

Two-dimensional waveguides etched for visible light and near infrared wavelength application frequently have high attenuation rates caused by scatterings due to surface irregularities [1]–[5]. Scattering loss should be substantially reduced at the long wavelength of 10.6 μm. We report here the successful experimental fabrication of two-dimensional GaAs waveguides by chemical etching. These waveguides are important to 10.6-μm integrated optics applications. For example, for electrooptical modulation, the RF electrode capacitance in the two-dimensional waveguide configuration, is less than the capacitance in the one-dimensional waveguide configuration; consequently, only small RF power ($p/\Delta f$ in the order of 0.01 W/MH) is needed to drive the two-dimensional modulator [6].

In our fabrication and evaluation process, one-dimensional waveguides were first fabricated by vapor phase epitaxial growth of GaAs thin film (using the group V hydride feed system and the HCl transport of Ga) on low resistivity n^+GaAs substrate. The thin film is typically 25 μm thick and the sample is typically $5 \times 2 \times 0.025$ cm in size. The attenuation rate of the one-dimensional waveguides is evaluated by exciting a specific guided wave mode with an input prism coupler and then coupling out the radiation in that mode some distance away by an output prism coupler. The slope of the line representing the output radiation intensity (with constant input CO_2 laser intensity) plotted on a logarithmic vertical scale as a function of the distance between two prisms plotted on a linear horizontal scale gives the attenuation of various modes. Typically, the attenuation rate of the TE_0 mode may vary from 1 db/cm to 3 db/cm for free carrier concentration $N_s \cong 10^{18}$ carriers per cubic centimeter in the n^+GaAs substrate and $N_f \cong 5 \times 10^{14}$ carriers per cubic centimeter in the GaAs film. For the sample VR5-422 the measured attenuation rate for the TE_0 mode is 4.1 db/cm while the attentuation rate for the TE_1 mode is 5 dB/cm.

Subsequently, the sample is first coated with SiO_2, 0.15 μm thick (using Emulsitone Silicafilm and subsequent heat treatment at 350°C) and then spin coated with AZ 1350 photoresist, about 0.5 μm thick. AZ 1350 is exposed in the usual manner through a suitable photo mask (made by conventional photolithography technique) to make an SiO_2 mask that will protect white areas in Fig. 1

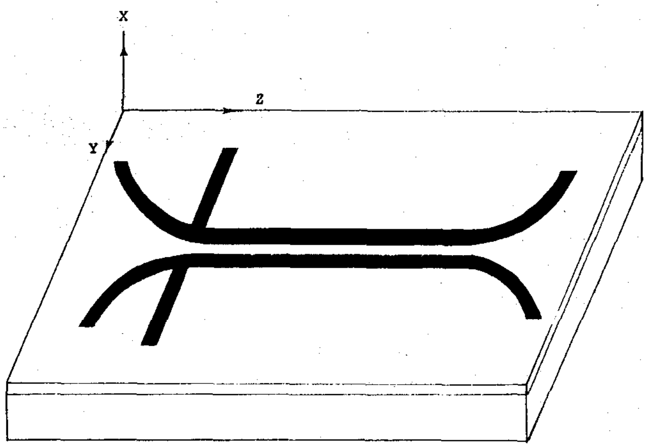

Fig. 1. Schematic diagram of an etched two-dimensional waveguide.

during chemical etching. Following that, the GaAs (dark area in Fig. 1) is etched about 25 μm deep by H_2SO_4:H_2O_2:H_2O (3:1:1) at 45°C for about 5 min; the SiO_2 mask is then removed by HF.

The resultant product schematically shown in Fig. 1 consists of a two-dimensional waveguide surrounded by deep etched grooves to isolate the waveguide from the surrounding mesa of GaAs. The two-dimensional waveguide has tapered transitions at both ends so that one-dimensional waveguide modes can be excited by the prism coupler and so that the taper will make a smooth transition from the one-dimensional waveguide modes to the two-dimensional waveguide modes. The surrounding mesa of GaAs is necessary to support the pressure of the prism coupler. The vertical deep groove cutting across the mesa shown in Fig. 1 is necessary to prevent radiation leaking from the input prism coupler to the output prism coupler through the surrounding mesa of GaAs. Fig. 2(a) shows a 500X magnification of a section of the etched waveguide where each large scale division corresponds to 2.2 μm in distance. Fig. 2(b) shows the profile of the waveguide monitored by Dektak. The surface irregularities caused by chemical etching are clearly much less than 1 μm.

We have been able to excite several E_{1q}^y and E_{2q}^y modes by setting the vertical angle of incident CO_2 beam with the input prism for $m = 0$ and $m = 1$ modes of one-dimensional waveguide. Modes having various values of q, the transverse mode order along the width of the two-dimensional waveguide, were excited by adjusting the horizontal angle between the input prism and the axis of the two-dimensional guide. When attenuation rates of the two-dimensional guide were evaluated by sliding the output prism coupler, we obtained 3.8 dB/cm for E_{1q}^y modes and 4.9 dB/cm for E_{2q}^y modes for small values of q.

This result demonstrated that no measurable increase in attenuation occurred for the two-dimensional waveguide modes E_{1q}^y and E_{2q}^y (with small q values) as compared to the TE_0 and TE_1 one-dimensional waveguide modes. The slight decrease in attenuation is probably caused by the fact that we have chosen a better section of the sample to make a two-dimensional waveguide. Similar results were obtained in sample VR5-424 where a 50-μm wide two-dimensional waveguide is fabricated. However, when a 25-μm-wide two-dimensional waveguide is fabricated on sample VR5-421 an increase of attenuation of 1 dB/cm occurred for the E_{1q}^y modes and an increase of attenuation of 6 dB/cm occurred for the E_{2q}^y modes.

In conclusion, we have demonstrated that conventional photolithography technique is adequate to yield low-loss two-dimensional GaAs waveguides for E_{1q}^y modes. The attenuation will increase significantly both when E_{pq}^y ($p \geqq 2$) modes are used and when the width of the waveguide is very narrow.

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