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YIG Resonator Circuit with Isolator Property and Its Application to a Gunn Diode Oscillator

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***Abstract*—This paper presents the analysis and experiment of a newly developed YIG resonator circuit with isolator property, which is constructed with a YIG sphere, three coupling loops, and a 3-dB stripline directional coupler. This YIG circuit can be used advantageously as the tuning element of a magnetically tunable oscillator. The circuit has an advantage in preventing frequency pulling and the variation of output power level of the oscillator due to a change in load condition because of the resonator circuit having isolator property at the same time.**

The design procedure and experiment of a magnetically tunable Gunn diode oscillator with the YIG circuit is also shown. It has been confirmed that the YIG circuit when applied to a tunable oscillator is quite useful.

I. Introduction

OSCILLATION frequency and output power level of an oscillator are usually affected by wave reflection from its load. In order to prevent such influences, a buffer amplifier is used in lower microwave frequency bands and an isolator or a circulator are required in higher microwave bands. A YIG resonator is commonly used as a magnetically tunable element in a wide-band microwave sweep oscillator. Therefore it is necessary to use additionally a wide-band isolator or circulator in such a sweep oscillator. Since these are disadvantageous in size and cost, it is desirable to use a YIG element which has both resonator and isolator properties at the same time. One of the authors already reported such a kind of waveguide type YIG resonator circuit [1].

The waveguide YIG circuit makes use of circularly polarized RF magnetic field in the plane spaced $\lambda g/4$ from the narrow wall of the waveguide in order to obtain isolator property. This waveguide YIG circuit, however, is bulky and is inferior in size and operational frequency bandwidth.

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Thus a new YIG resonator circuit with isolator property has been developed which is constructed by using a YIG sphere resonator in conjunction with a 3-dB stripline directional coupler. This paper presents theoretical analysis and experimental confirmation of the new YIG resonator circuit with isolator property, followed by the design and experiment of a magnetically tunable Gunn diode oscillator using the YIG circuit. The value of the calculated scattering matrix of the YIG circuit agrees well with experimental results, and the magnetically tunable Gunn diode oscillator shows good improvement in frequency pulling and in eliminating output power level change due to load variation as compared with the usual magnetically tunable Gunn diode oscillator.

II. YIG Resonator Circuit with Isolator Property

Fig. 1 is a schematic of a magnetically tunable Gunn diode oscillator with a YIG resonator circuit having isolation properties. A YIG sphere is placed at the intersection of three semiloop axies. Two loops connected to ports 2′ and 3′ of a 3-dB directional coupler are placed orthogonally, similar to a nonreciprocal filter [2], [3]. The other semiloop at port 1 is placed on the opposite side of a metal plate for shielding. These loops are not coupled to each other when the YIG sphere is not resonant. Fig. 2 is the equivalent circuit in regards to ports 1, 2′, and 3′ of the YIG resonator part itself. The impedance matrix of the YIG resonator part is given by considering the equivalent circuit and a nonreciprocal phase shift, so the scattering matrix $[S_Y]$ of the equivalent circuit is obtained by converting this impedance matrix into a scattering matrix. Thus the obtained scattering matrix $[S_Y]$ is as follows:

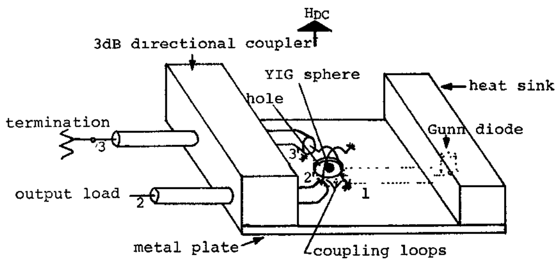

Fig. 1. Schematic of a magnetically tunable Gunn diode oscillator with isolator property.

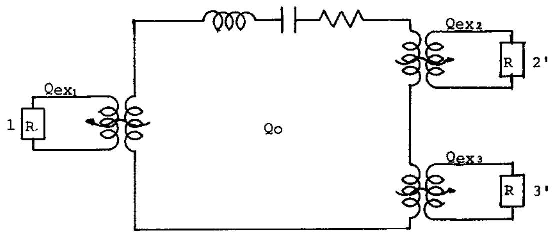

Fig. 2. Equivalent circuit of YIG resonator with three coupling loops.

$$S_{y11}=\frac{1}{\Delta}\left[(1-\delta_1)(1+\delta_2)(1+\delta_3)-j\frac{1}{A}\cdot\left\{\frac{(1+\delta_2)(1+\delta_3)}{Q'_{ex1}}-\frac{(1+\delta_3)(1-\delta_1)}{Q'_{ex2}}-\frac{(1-\delta_1)(1+\delta_2)}{Q'_{ex3}}\right\}\right]$$

$$S_{y12}=\frac{1}{\Delta}\frac{2}{A}j\frac{1+\delta_3}{\sqrt{Q'_{ex1}Q'_{ex2}}}$$

$$S_{y13}=\frac{1}{\Delta}\frac{2}{A}\frac{1+\delta_2}{\sqrt{Q'_{ex1}Q'_{ex3}}}$$

$$S_{y21}=\frac{1}{\Delta}j\frac{2}{A}\frac{1+\delta_3}{\sqrt{Q'_{ex2}Q'_{ex1}}}$$

$$S_{y33}=\frac{1}{\Delta}\left[(1+\delta_1)(1+\delta_2)(1-\delta_3)-j\frac{2}{A}\cdot\left\{-\frac{(1+\delta_2)(1-\delta_3)}{Q'_{ex1}}-\frac{(1-\delta_3)(1+\delta_1)}{Q'_{ex2}}+\frac{(1+\delta_1)(1+\delta_2)}{Q'_{ex3}}\right\}\right]$$

$$\Delta=1+j\frac{1}{A}\left(\frac{1}{Q'_{ex1}}+\frac{1}{Q'_{ex2}}+\frac{1}{Q'_{ex3}}\right)+\delta_1\cdot\left\{1+j\frac{1}{A}\left(\frac{1}{Q'_{ex2}}+\frac{1}{Q'_{ex3}}\right)\right\}+\delta_2\left\{1+j\frac{1}{A}\left(\frac{1}{Q'_{ex3}}+\frac{1}{Q'_{ex1}}\right)\right\}$$
$$+\delta_3\left\{1+j\frac{1}{A}\left(\frac{1}{Q'_{ex1}}+\frac{1}{Q'_{ex2}}\right)\right\}+\delta_1\delta_2\cdot\left(1+j\frac{1}{A}\frac{1}{Q'_{ex3}}\right)+\delta_2\delta_3\left(1+j\frac{1}{A}\frac{1}{Q'_{ex1}}\right)+\delta_3\delta_1\left(1+j\frac{1}{A}\frac{1}{Q'_{ex2}}\right)+\delta_1\delta_2\delta_3$$

$$A=\left(\frac{\omega_r}{\omega}\right)^2-1+j\frac{\omega_r}{\omega}\frac{1}{Q_0}\qquad \frac{1}{Q_L}=\frac{1}{Q_0}+\frac{1}{Q_{ex1}}+\frac{1}{Q_{ex2}}+\frac{1}{Q_{ex3}}$$

$$\delta_1=\frac{j\omega L_1}{R}\qquad \delta_2=\frac{j\omega L_2}{R}\qquad \delta_3=\frac{j\omega L_3}{R}$$

$$\frac{1}{Q'_{ex1}}=\frac{1-\delta_1^2}{Q_{ex1}}\qquad \frac{1}{Q'_{ex2}}=\frac{1-\delta_2^2}{Q_{ex2}}\qquad \frac{1}{Q'_{ex3}}=\frac{1-\delta_3^2}{Q_{ex3}} \tag{1}$$

where ω_r is a resonant angular frequency, Q_L is the loaded Q of the YIG resonator, Q_0 is the unloaded Q of the resonator, and Q_{ex1}, Q_{ex2}, and Q_{ex3} are the external Q of port 1, 2′, and 3′, respectively. R is an external termination resistance. L_1, L_2, and L_3 are self-inductances of the loops, respectively. When the two ports of the YIG resonator part are connected to ports 2′ and 3′ of the 3-dB directional coupler, respectively, the scattering matrix $[S_{DY}]$ of the YIG resonator circuit in regards to ports 1, 2, and 3 in Fig. 1 is given by considering the scattering matrixes $[S_Y]$ and that of the 3-dB directional coupler [3]. The scattering matrix $[S_{DY}]$ is obtained as following.

$$[S_{DY}]=\begin{bmatrix} S_{y11} & S_{y12}\alpha+S_{y13}\beta & S_{y12}\beta+S_{y13}\alpha \\ S_{y12}\alpha+S_{y31}\beta & S_{y22}\alpha^2+S_{y33}\beta^2 & (S_{y22}+S_{y33})\alpha\beta+S_{y23}(\alpha^2-\beta^2) \\ S_{y12}\alpha+S_{y31}\beta & (S_{y22}+S_{y33})\alpha\beta+S_{y23}(\beta^2-\alpha^2) & S_{y22}\beta^2+S_{y33}\alpha^2 \end{bmatrix} \tag{2}$$

$$S_{y22}=\frac{1}{\Delta}\left[(1+\delta_1)(1-\delta_2)(1+\delta_3)-j\frac{1}{A}\cdot\left\{-\frac{(1-\delta_2)(1+\delta_3)}{Q'_{ex1}}+\frac{(1+\delta_3)(1+\delta_1)}{Q'_{ex2}}-\frac{(1+\delta_1)(1-\delta_2)}{Q'_{ex3}}\right\}\right]$$

$$S_{y23}=\frac{1}{\Delta}\frac{2}{A}\frac{1+\delta_1}{\sqrt{Q'_{ex2}Q'_{ex3}}}$$

$$S_{y31}=\frac{-1}{\Delta}\frac{2}{A}\frac{1+\delta_2}{\sqrt{Q'_{ex3}Q'_{ex1}}}$$

$$S_{y32}=\frac{-1}{\Delta}\frac{2}{A}\frac{1+\delta_1}{\sqrt{Q'_{ex3}Q'_{ex2}}}$$

where k is the coupling coefficient, α is k, and β is $-j\sqrt{1-k^2}$. When considering an ideal 3-dB coupler, k is $1/\sqrt{2}$, so α is $1/\sqrt{2}$, and β is $-j1/\sqrt{2}$. This matrix indicates that the circuit which is seen from port 1 is considered to act as a usual YIG resonator. Therefore, when an active element is connected to port 1, a magnetically tunable oscillator is realized.

When $Q_{ex2}=Q_{ex3}$, the element S_{12} of $[S_{DY}]$ is equal to zero at resonant frequency and S_{21} of $[S_{DY}]$ is not equal to the S_{12}, meaning that the YIG resonator circuit has isolator property, the power from port 2 is not coupled to port 1, but the power from port 1 is led to port 2. The measured absolute values of the elements of $[S_{DY}]$ in relation to tuning frequency are shown in Fig. 3. From

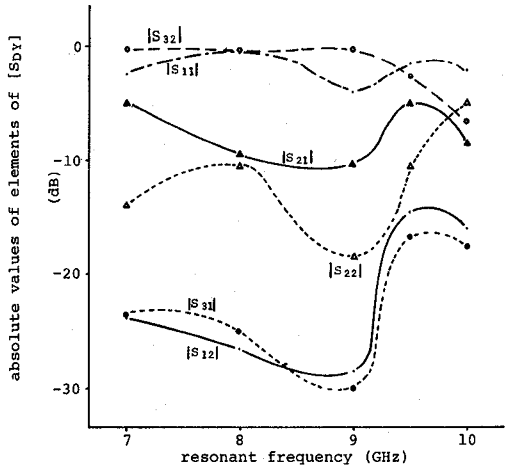

Fig. 3. Measured absolute value of the elements of $[S_{DY}]$ versus resonant frequency.

TABLE I
COMPARISON OF THE DIRECTLY MEASURED VALUE WITH THE CALCULATED VALUE OF THE ELEMENT OF $[S_{DY}]$

-0.75	-27	-9.5	
-10.0	-10.1	-1.1	in dB
-26	-0.9	-10.0	

(a) absolule value of $[S_{DY}]$ measured directly.

-0.67	-21	-11.0	
-10.6	-10.3	-1.1	in dB
-21	-0.97	-9.7	

(b) absolute value of $[S_{DY}]$ calculated.

this figure, the difference of $|S_{21}|$ from $|S_{12}|$ is more than 15 dB from 7 to 9 GHz, but above 9 GHz, the difference degrades somewhat gradually. This is caused by the characteristics of the 3-dB directional coupler being used.

The coupler being used gradually does not show 3-dB operation above 8 GHz and above 9 GHz abruptly. This is due to the fact that the coupler used has the center frequency of 6 GHz. The calculated absolute value of the elements of $[S_{DY}]$ from (2) by using measured value of Q_0, Q_{ex1}, Q_{ex2}, Q_{ex3}, and the elements of $[S_D]$ is compared in Table I with that measured directly at the resonant frequency of 8 GHz. This result means that the calculated absolute value of $[S_{DY}]$ shows fairly good agreement with that measured directly in consideration of error accompanying the measured value. Fig. 4 shows resonance frequency admittance loci of the YIG resonator circuit at port 1 as a parameter of an applied dc magnetic field. Resonance frequency is 8–10 GHz. The diameter of the YIG sphere being used is 1.5 mm and the saturation

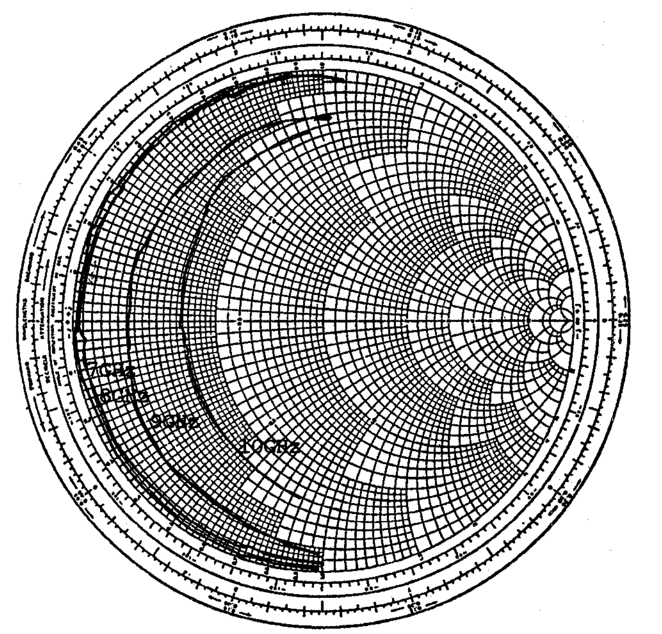

Fig. 4. Frequency loci of YIG resonator circuit at port 1, YIG sphere of $4\pi Ms = 1780$ G, and 1.5 mmϕ.

magnetization is 1780 G. These loci show that the characteristics of the resonance curves are reasonable for the low frequency band. There are some spurious responses on these loci. This is caused by coupling the YIG sphere to the loop rather strongly. Spurious resonances generally can cause frequency hopping and fine grained variations in frequency tuning and in noise properties. But spurious resonance in this experiment was too small to cause this kind of effect.

The nonlinear effect must be considered when such a YIG resonator is used as a frequency tunable element. The output power P_{out} toward the load is given from the definition of Q_{ex}

$$P_{\text{out}} = \frac{\omega_0 W}{Q_{ex}} \tag{3}$$

where W is the energy stored in the YIG sphere and ω_0 is a resonant angular frequency. By considering the relation of the energy stored and the RF magnetic field h, the power from port 2 toward the load is obtained as follows.

$$P_{\text{out}} = \frac{1}{2}\omega_0 \frac{Q_0}{Q_{ex}} \chi^2 \frac{\Delta H}{Ms} V_f h^2 \tag{4}$$

where V_f is the volume of the YIG sample, ΔH is the magnetic half width, and Ms is the saturation magnetization of the YIG sample. This equation gives the output power level of the oscillator at the critical RF magnetic field level h_c. It is estimated that the power level at the critical field h_c for the YIG circuit is about 22 dBm [4]. The nonlinear effect of the resonator was examined by measuring the output power at port 2 when input power applied at port 1 is increased. The experimental result shows that no nonlinear effect occurs up to 20 dBm in output power. Judging from the value estimated in the above, this result is reasonable. Thus in consideration of the experimental result in Section III, it can be said that the limitation of the oscillator output power is due not to the nonlinear effect of the YIG, but rather to the characteristics of the diode being used.

III. Magnetically Tunable Gunn Diode Oscillator with the YIG Resonator Circuit

A magnetically tunable Gunn diode oscillator using the above mentioned YIG resonator circuit with isolator property and Gunn diode has been designed and tested experimentally. The Gunn diode is connected to port 1 and a matched termination to port 3, as shown in Fig. 1. The output power of the oscillator is led from port 2. A semiloop at port 1 is tightly coupled to a YIG sphere. One end of the semiloop is grounded in a distance as short as possible.

The loop is a ribbon 3 mm in width, with a diameter of 2 mm. The YIG sphere is the same as the one described in Part II of this paper. The Gunn diode being used is an AEI type DI 1281G. The region of oscillation is given by $|1/\Gamma_A| < |\Gamma_R|$ and $\arg \Gamma_A + \arg \Gamma_R = 0$ where Γ_A and Γ_R are the reflection coefficients of the active diode circuit and the resonator circuit, respectively. The designing of the oscillator [5] is done by measuring both the inverse of the reflection coefficient of the Gunn diode and the frequency loci of the YIG resonator circuit from port 1. The $1/\Gamma_A$ measurement is done by using a Hewlett-Packard microwave network analyzer, because the value of $1/\Gamma_A$ can be measured directly by transposing its test and reference ports of the frequency converter in the analyzer. The values of $1/\Gamma_A$ and Γ_R are measured by the equipment having a 50-Ω characteristic impedance, so the impedance of the line connecting the Gunn diode to the loop is chosen to be 50 Ω.

An example of a measured value of $1/\Gamma_A$ is shown in Fig. 5 in the frequency range from 7 to 10 GHz. The resonance loci are shown in Fig. 4. By overlapping these two curves, the frequency range of oscillation can be estimated. There is found to be a possibility of oscillation in the 7- to 10-GHz frequency range. Experimental results for the magnetically tunable Gunn diode oscillator are shown in Fig. 6. In this figure curve 2 is the output power level of the oscillator at output port 2, and curve 3 is the leakage power level to the matched termination of port 3. The output power level of the oscillator is about 10–16 dBm in the 7–9.2-GHz frequency range, and degrades gradually above 9.2 GHz. The relation between oscillation frequency and an applied dc magnetic field is linear from 7 to 10 GHz, and the power level for spurious frequencies is below −50 dBm. Curves A and B indicate the frequency variation Δf due to phase change of the output load when the reflection coefficient of the load $|\Gamma| = 1$. Curve A shows the data for the YIG resonator circuit with isolator property, and curve B is the case of the usual YIG resonator only. In the case of the YIG resonator circuit with isolation property the value of Δf is below 2 MHz in

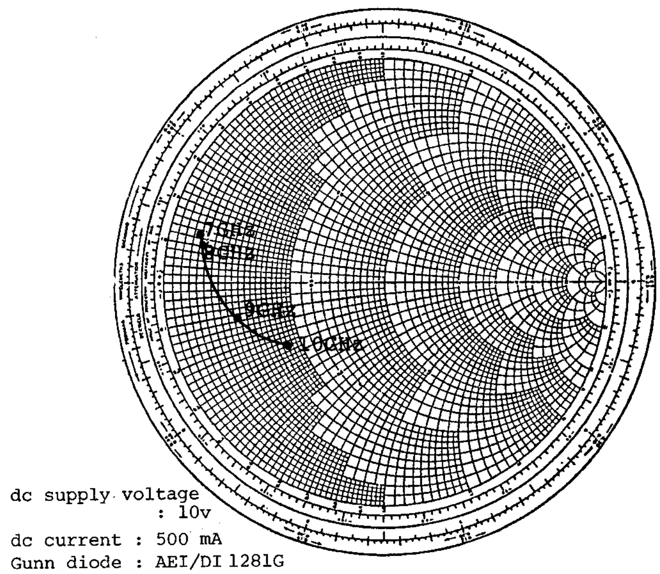

Fig. 5. $1/\Gamma_A$-locus of Gunn diode being used.

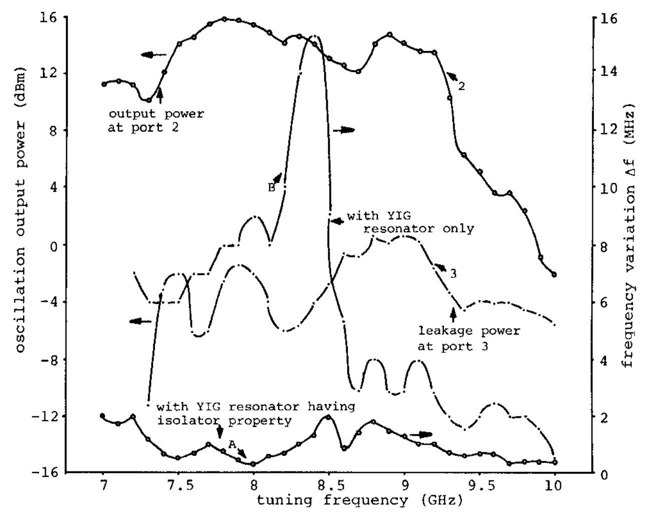

Fig. 6. Frequency characteristics of oscillator output power level and frequency variation.

range. In the case where the YIG resonator only is used the value of Δf varies up to 15 MHz. As shown in Fig. 7 in the case of the only the YIG resonator being employed, output power varies within a 10-dBm range and when loading becomes critical the oscillator ceases operating or jumps to a different frequency. In the newly developed YIG circuit, power output variation of the oscillator is held to a level below 1 dB in range, and oscillation is stable despite changes in the load condition of the oscillator.

IV. Conclusion

It has been ascertained that the YIG resonator circuit with isolator property is useful for preventing frequency pulling and power level variation of an oscillator due to changes in load condition, and is advantageous in size and cost. The calculated scattering matrix of the YIG circuit is

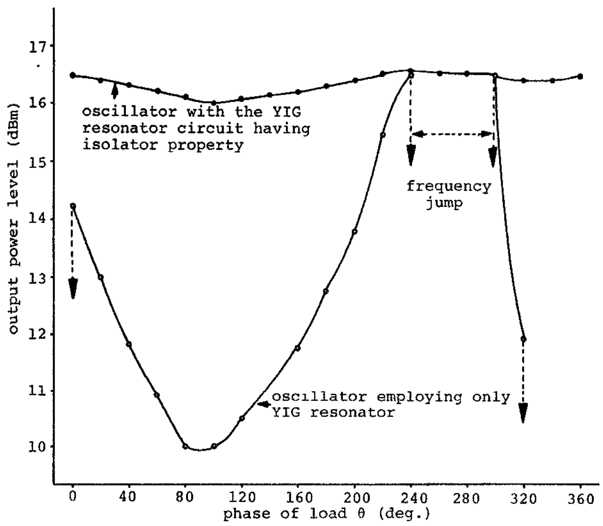

Fig. 7. Oscillation power level as a function of phase θ of load at $|\Gamma| = 1$, 8.2 GHz.

confirmed by the experiment. The tuning frequency range of the experimental oscillator is restricted by the characteristics of the 3-dB directional coupler being used, so a tunable frequency range of the oscillator with the circuit can be made wider by utilizing a wider frequency band 3-dB directional coupler. The proposed YIG resonator circuit will be naturally applicable to other negative resistance type oscillators like that of an IMPATT diode oscillator, but for the application to the more high power oscillator, some careful considerations about the nonlinear effect of YIG sample will be required.

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Reflection of Magnetostatic Forward Volume Waves by a Shallow-Grooved Grating on a YIG Film

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Abstract—**The magnetostatic forward volume wave (MSFVW) reflection characteristics of a uniform grating of shallow grooves etched on the planar surface of an epitaxial YIG film are treated using an approach which integrates field theory with the coupled-mode approach. The MSFVW reflectivity per groove is found to be comparable to the reflectivity of magnetostatic surface waves (MSSW's) and thus is found to be significantly large considering that the volume waves are reflected by surface-localized and shallow grooves.**

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I. Introduction

A CLASS OF high-performance surface-acoustic-wave (SAW) devices such as resonators and bandpass and chirp filters which are based on the use of shallow-grooved reflector arrays has recently emerged, see for example [1]. A potential exists for the realization of similar devices operating at higher frequencies based on the use of magnetostatic waves in epitaxial YIG films. Recent experimental [2] and theoretical [3]–[5] studies have shown that magnetostatic surface waves (MSSW's) on a YIG film are reflected significantly more strongly by a groove than are SAW's by an equivalent groove on a

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