"TWO-PORT" MAGNETOSTATIC WAVE RESONATORS UTILIZING PERIODIC REFLECTIVE ARRAYS

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ABSTRACT

Two-port magnetostatic wave, surface wave resonators utilizing periodic etched groove array reflectors have been fabricated on LPE YIG and evaluated in S-band. Loaded Q's of greater than 800 have been observed with octave bandwidth tunability. Theory based on a cascaded transmission line model has shown good agreement with the experimental results. Loaded Q's approaching the material Q of >3000 appear feasible. Cascading of resonators to obtain better off-resonance isolation and complex filter function is feasible.

Introduction

Surface Acoustic Wave (SAW) resonator filters, which operate very effectively in the VHF/UHF range, experience significant technical difficulties[1] as the operating frequency is increased above 1 GHz. In particular, operation above 3 GHz requires submicron device dimensions and exhibits large propagation losses. Tunable, high Q, low loss yttrium iron garnet (YIG) sphere resonator filters operate well at microwave frequencies, but fabrication procedures are tedious and expensive. As a result, complex filter functions are difficult to realize with this technology.

This paper describes a new resonator technology, with similarities to SAW devices, which is based on Magnetostatic wave (MSW) propagation in low line width ($\Delta H < 0.5 Oe$) thin film YIG grown by liquid phase epitaxy (LPE).[2] MSW are slow, dispersive, magnetically dominated electromagnetic waves propagating in a magnetically biased ferrite material at microwave frequencies (1 - 20 GHz). MSW propagation in a free ferrite slab has been treated by Damon and Eschbach,[3] who considered three principal bias field, $\overline{H}$, orientations with the wave vector, $\overline{k}$, in the plane of the slab. Of particular interest for this work is the magnetostatic surface wave (MSSW) occurring when $\overline{H} \times \overline{n}$ is parallel to $\overline{k}$ where $\overline{n}$ is the unit normal to the slab plane. The MSSW is characterized by magnetic energy which is confined primarily to either surface of the ferrite slab depending on the propagation direction relative to the bias field orientation. The dispersion and delay characteristics for MSSW are presented in Fig. 1.

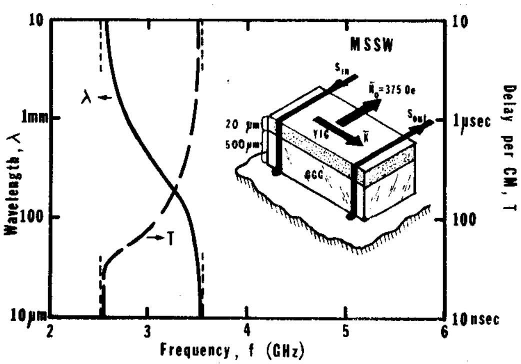

FIG. 1. DISPERSION CHARACTERISTICS AND GROUP DELAY OF MAGNETOSTATIC SURFACE WAVES (MSSW) IN A YIG PLATE WITH A GROUND PLANE IN PROXIMITY

As in the SAW case, a resonator consists of a pair of wavelength selective periodic reflecting arrays separated by a delay section. These elements are arranged relative to the propagation path to form a resonator cavity and a means for transduction is established within the cavity. The single port MSSW reflecting array resonator of this type has been reported by Collins et.al.[4] This paper treats the two-port MSSW reflecting array resonator with an input-output transducer pair located in the resonant cavity; the geometry of this device is shown in Fig. 2. This structure is of particular interest due to its inherent isolation between input and output ports and ease of application in filter and oscillator systems. These resonators retain the desirable features of tunability and microwave frequency operation associated with previous YIG technology; however, as seen from Fig. 1, submicron wavelengths are not required so conventional microelectronics fabrication techniques are used for device fabrication.

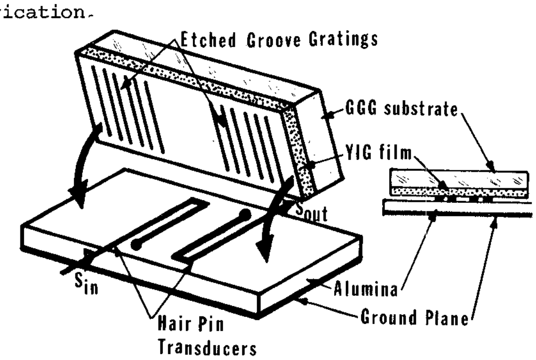

FIG. 2. SCHEMATIC OF "TWO-PORT" MAGNETOSTATIC WAVE RESONATOR

Modeling and Theory

Since the MSSW corresponds to a limiting case of a TE electromagnetic mode, gratings in the reflecting array resonator can be modeled in terms of cascaded equivalent transmission line sections. Such modeling as applied to SAW filters and acoustic dispersive delay lines has been presented by Sittig and Coquin.[5] For MSSW, however, dispersion, propagation loss and nonreciprocity of propagation due to the proximity of ground planes must be included. In general, each array within the resonator can be considered to be a cascade of grating elements and the resonator cavity treated as two such arrays spaced by an appropriate delay section. The inverse transmission matrix for a line of length L has been presented by Collins et.al.[6] along with a discussion of Storch's[7] method for calculation of overall transfer matrices for individual arrays. For nonreciprocal propagation this method is used to calculate the overall forward and reverse transmission matrices $(T)_F$, $(T)_R$ for an array. Denoting these matrices for an N element grating as

$$(T)_F = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{Bmatrix} a & b \\ c & d \end{Bmatrix}^N \qquad (1)$$

and

$$(T)_R = \begin{pmatrix} E & F \\ G & H \end{pmatrix} = \begin{Bmatrix} e & f \\ g & h \end{Bmatrix}^N \tag{2}$$

and a ... h are the transmission matrix coefficients for the forward and reverse line section. The various reflection and transmission coefficients are then evaluated as:

$$\tau_F = \frac{Z_F - Z_R}{Z_F A + B - Z_R(Z_F C + D)} \tag{3}$$

$$\rho_F = \frac{Z_R(D - A + Z_F C - B/Z_F)}{Z_F A + B - Z_R(Z_F C + D)} \tag{4}$$

$$\tau_R = \frac{Z_R - Z_F}{Z_R E + F - Z_F(Z_R G + H)} \tag{5}$$

and

$$\rho_R = \frac{Z_F(H - E + Z_R G - F/Z_R)}{Z_R E + F - Z_F(Z_R G + H)} \tag{6}$$

The corresponding insertion and reflection losses can be obtained from finding $-20 \log_{10}$ of the magnitudes of these factors. These quantities do not account for transducer loading effects.

The resonator cavity can be considered equivalent to a microwave Fabry-Perot resonator[8] if the concept of an effective mirror plane is introduced.[9] The distance, d, the effective mirror plane is located into an array can be determined using the reactance slope, the rate of phase change of the reflection factor, at the insertion loss notch;

$$d = \frac{1}{2v_g} \frac{d\phi}{d\omega} \tag{7}$$

where v_g is the group speed, ϕ the phase and ω the radian frequency. For a given resonator design the effective resonator cavity spacing is just $L = d_F + d_R + \ell$ where ℓ is the reflecting array spacing and the subscripts denote the forward and reverse wave factor; the mode spacing for the resonator is

$$\Delta f_m = 1/L(T_F + T_R) \tag{8}$$

where T_F and T_R are respectively the group delay times per unit length. The remaining parameter of interest is the resonator quality factor or Q, which is equivalent to the reciprocal fractional bandwidth, $\omega_o/\Delta\omega$[9] where $\Delta\omega$ is the half-power bandwidth for the resonance at ω_o. This identification permits determination of Q's directly from insertion loss versus frequency characteristics for both theory and experiment. Grouping individual resonator power losses into array, propagation and transducer losses give a loaded quality factor Q_L as

$$\frac{1}{Q_L} = \frac{1}{Q_u} + \frac{1}{Q_{ext}} \tag{9}$$

where the external quality factor Q_{ext} is associated with transducer loading and the unloaded quality factor Q_u is the parallel combination of the array quality factor Q_r and the material or propagation quality factor Q_m. Q_r can be obtained in terms of the effective cavity length, d, and the geometric mean of the forward and reverse reflection factors ρ as[9]

$$Q_r = \frac{2\pi d}{\lambda_o(1 - |\rho|^2)} \tag{10}$$

where λ_o is the resonant wave length. The material quality factor Q_m is related to the wave attenuations and group speeds as

$$Q_m = \omega_o/2\alpha v_g \tag{11}$$

where α and v_g are respectively the associated geometric mean values for forward and reverse propagation.

Experimental Results

A number of two-port MSSW reflecting array resonators have been designed, fabricated and tested. These devices utilize a pair of spatially periodic, chemically etched groove arrays as reflectors. Typically, the LPE YIG sample is a 3 mm wide, 25 mm long, 10-20 μm thick film on a 0.5 mm thick gadolinium gallium garnet (GGG) substrate. Arrays are formed photolithographically by defining the required pattern in a Silox grown SiO_2 mask and etching array grooves in the YIG using orthophosphoric acid at 200°C. The YIG sample is then mechanically placed into contact with the transducer pair in a "flipped" configuration as indicated in Fig. 2. The hair pin input/output transducers are formed in μm thick aluminum on a alumina (Al_2O_3) substrate and fed by 50 Ω microstrip. Each hair pin loop is composed of two parallel 35 μm wide strips with 150 μm center-to-center spacing; one end of each transducer is shorted through the aluminia to a ground plane on the opposite face of the substrate. The resonators are designed to operate at a convenient 300 μm wave length.

Three measurements are made for each resonator: First, the frequency response characteristic and unloaded quality factor Q_u are obtained by measuring the transmission through the reflecting array resonator with a pair of transducers placed on the cavity axis but outside the resonator structure. Fig. 3 shows a typical resonator insertion loss notch for both theory and experiment utilizing this method; Q_u for either theory or experiment is obtained from the fractional bandwidth as measured from the corresponding curve. Second, the loaded quality factor Q_L is measured from the insertion loss versus frequency characteristic obtained with a pair of transducers located on the cavity axis between the reflecting arrays. Fig. 4 shows a typical resonator insertion loss characteristics. In the coupled case the YIG is directly on the transducer pair and for the decoupled case the YIG is spaced off the transducers by a 35 μm thick dielectric. The resonator structure consists of a pair of 40 groove arrays with 71.25 μm wide, 0.28 μm deep grooves and 75 μm lands separated by 3600 μm on a 10 μm thick film. Resonance isolation is not as good as possible due to the lack of proper terminations for waves transmitted out of the resonator through an array and reflected from the sample ends back to the resonator.

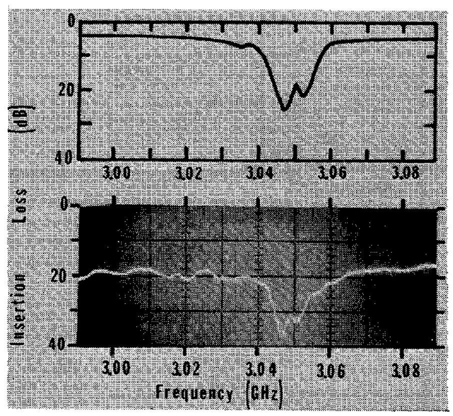

FIG. 3. THEORETICAL (TOP) AND EXPERIMENTAL INSERTION LOSS (db) VS FREQUENCY (GHz) CHARACTERISTICS OF TRANSMISSION THROUGH A RESONATOR STRUCTURE

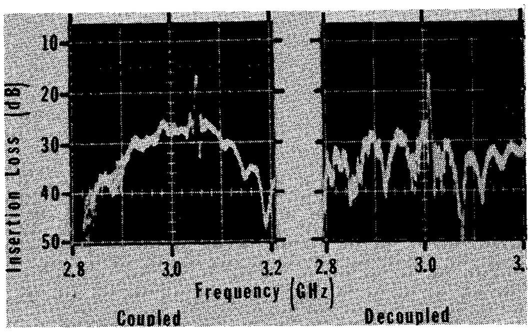

FIG. 4. "TWO-PORT" RESONATOR RESPONSE CHARACTERISTICS FOR INPUT/OUTPUT TRANSDUCERS IN DIRECT CONTACT WITH THE YIG FILM AND DECOUPLED BY A 35μm DIELECTRIC LAYER

All measurements are performed with a HP 8410 B network analyzer at S-band for convenience and the Q measurements are performed so that the direct transmission between transducers is via the "bottom surface" wave. Use of the "bottom surface" wave further decouples the resonator and reduces off-resonance feed-through. A summary of the results for resonator Q measurements and comparison with theory are shown in Table I.

Design	Theory		Measured	
	Q_u	Q_m	Q_u	Q_L
Coupled	883	5670	825	775
Decoupled	883	5670	825	805

Table I. Comparison of Theoretical and Measured Q Values for Two Resonator Designs $\Delta H = .15$ oe

The agreement of the values presented in Table I is good and the physical consistency is excellent. The third and final resonator measurement is an examination of the tuning characteristic obtained by variation of the bias field intensity. A typical multiple exposure trace for the tuning of the coupled resonator over the 1 GHz band from 2.5 to 3.5 GHz is shown in Fig. 5. The relatively unchanged response for the resonator as it is tuned has also been observed over a 2 GHz band from 2-4 GHz.

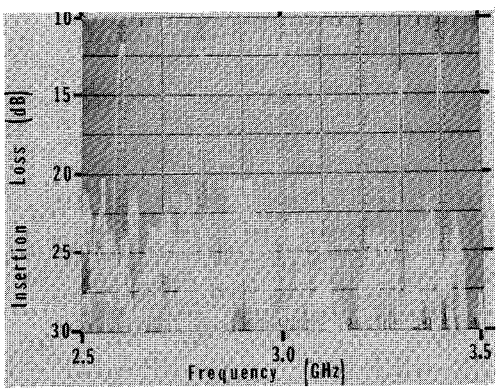

FIG. 5. FIELD TUNING CHARACTERISITCS OF AN MSSW "TWO-PORT" RESONATOR

Conclusions

Two-port reflecting array resonators utilizing magnetostatic surface waves propagating in LPE YIG films and periodic etched groove reflecting structures have been experimentally demonstrated and theoretically analyzed. Loaded Q's of greater than 800 have been observed and are consistent with theoretical predictions. With suitable design and fabrication optimization, loaded Q's of greater than 1000 should be readily realized. The resonators are bias field tunable over more than an octave bandwidth in S-band. Off-resonance isolation must be improved by inclusion of better terminations and optimum transducer/film thickness choice.

In principle, these resonators can be constructed for operation at any frequency in the 1 - 20 GHz band. The geometry of the resonators is suitable for cascading either to reduce out of band spurious response as in the SAW or to realize complex tunable filter functions.

Acknowledgments

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