frequencies of the isosceles triangular microstrip resonators with good accuracy.

The isosceles triangular microstrip resonator has a wide variety of applications in resonator and filter networks. The apex angle and triangle height provide additional flexibility in the design. They can also be used as a radiating element in various array applications.

The nonavailability of an adequate analysis and design data on triangular shape has so far precluded the possibility of their application as a network element at microwave frequencies. The theoretical data presented in this paper will provide a designer an insight into the controllability of various governing parameters.

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Magnetostatic Wave Dispersive Delay Line

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Abstract —**The physical limits of the interdigital transducer (IDT) implementation for surface acoustic wave (SAW) devices beyond VHF/UHF have restricted their use in microwave systems. Inherent dispersion of magnetostatic wave (MSW) devices is suitable for signal processing directly at microwave frequencies. Dispersion enhancement tests performed on MSW delay lines confirm their suitability to an *S*-band simultaneous pulse separator for EW receiver applications.**

I. Introduction

Ability to produce frequency dependent phase delays and dispersion, in UHF and VHF bands, enabled the development of signal-processing components such as dispersive filters, delay lines, pulse compressors, pulse expanders, convolvers, and correlators [1], [2]. High dispersion in small physical dimensions is commonly achieved using SAW technology, where the acoustic-wave velocity is of the order of 10^5 cm/s. Upper frequency limitations stem from the photolithographic ability to resolve narrow line widths and gaps with nearly one hundred percent yield. The state-of-the-art devices operate up to 1.8 GHz and seemingly approach the upper frequency limit [3].

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Since the magnetostatic wave propagation velocities are at least an order of magnitude higher than those of SAW, it should be possible to achieve much higher frequency operation maintaining the same line resolution. It is of great advantage, however, that MSW launching could be achieved through a single line geometry [4].

Intrinsically dispersive characteristics of MSW, although nonlinear, are of immediate use in EW applications, such as a simultaneous pulse separator [5]. It has been observed that nonchannelizeed receivers often read incorrect information in the presence of simultaneous signals [6]. The simultaneous signal separator can be used in conjunction with an inexpensive IFM receiver to improve the probability of intercept in a dense EW environment. For this purpose, a highly dispersive delay line is required to separate in time-domain simultaneous signals differing in frequency. Typically, simultaneous signals 100 MHz apart may require more than 30-ns time separation for individual detection.

Quasi-TEM bulk or planar structure provide insufficient dispersion sensitivity, dispersion per unit length, for realization in small size. MSW dispersion at microwave frequencies is ideally suited for this application. Additionally, the MSW dispersion characteristics can be linearized to obtain upchirp or downchirp, enabling extensive signals processing in microwave frequencies [7]. A brief summary of MSW modes is presented in Section II. Experimental results of coupling and dispersion in a MSSW device and the temperature effects on the delay characteristics are discussed in Section III. Section IV discusses dispersion modification techniques and is followed by a summary in Section V.

II. Magnetostatic Waves

Magnetostatic waves are inherently dispersive, magnetically dominated electromagnetic waves. The three fundamental wave categories are: 1) Magnetostatic Surface Waves (MSSW); 2) Magnetostatic Forward Volume Waves (MSFVW); and 3) Magnetostatic Backward Volume Waves (MSBVW). Recent development in liquid-phase epitaxial growth techniques for high-quality bubble memory YIG films on Gadolinium Gallium Garnet (GGG) substrates revived the interest in MSW for microwave applications. MSW devices can operate at frequencies in excess of 20 GHz with associated losses below 25 dB/μS. Associated dispersion and time delays of 100 ns/cm can be readily achieved.

The particular MSW wave that can exist in a YIG-film geometry is determined solely by the orientation of a bias field relative to the YIG film and propagation direction. When the bias field is normal to the YIG film, only MSFVW's can exist. When the bias field lies in the plane of the YIG film, MSBVW's exist for the film, direction parallel to the propagation vector $\boldsymbol{k}$ and MSSW exist for the field normal to the direction of propagation. Among the three modes, only MSBVW's exhibit negative dispersion, downchirp, characteristics (i.e., the phase and group velocities have contra-directed components along each other). The theoretical propagation bandwidth limits for the three modes are defined by k values of 0 and ∞. The frequency range for the volume waves is

$$f_0 < f < [f_0(f_0+f_m)]^{1/2} \tag{1}$$

where $f_0 = \gamma\mu_0 H$ is the gyro frequency and $f_m = \gamma\mu_0 M_s$ is the magnetization frequency. The MSSW propagation band is located immediately above the volume wave spectrum, with frequency bounds given as

$$[f_0(f_0+f_m)]^{1/2} < f < f_0 + \frac{f_m}{2} \quad (2)$$

for a surface wave localized at the unmetallized YIG surface, and

$$[f_0(f_0+f_m)]^{1/2} < f < f_0 + f_m \quad (3)$$

for a wave localized at the metallized surface.

Wideband efficient transduction to MSW in YIG films is possible using narrow microstrip couplers. The MSW dispersion characteristics can be modified by control of physical parameters such as ground-plane spacing, bias field, and path modification.

III. Dispersion Results

For the particular application of a simultaneous pulse separator, maximum dispersion is desired. Dispersion measurements were carried out for all the three MSW modes at S-band.

Results reported here pertain to a 14-μm thick YIG film MSSW device. Simple 3-mm-long, 50-μm-wide shorted microstrip couplers were used for input and output ports. The YIG film was placed on top of a 0.010-in-thick alumina substrate having an etched transducer on one side and a ground plane on the other side. Initial S_{11} and S_{22} measured at input and output ports, respectively, were significantly reduced over an 800-MHz bandwidth at S band using simple single stub matching networks (Fig. 1 and 2). Time delay versus frequency was measured for three different films in order to confirm experimentally the effect of YIG-film thickness. Their responses plotted in Fig. 3, were found to be in good agreement with theory. Thinner films offer larger time delays and dispersion sensitivity. Hence, YIG films, grown using the techniques developed for thin-bubble memory films, can find direct application in highly dispersive delay lines.

Use of a delay line comprising a 3-μm-thick YIG film provided a separation of signals, 150 MHz apart, by at least 40 ns.

The effect of temperature on delay time versus frequency has been measured (Fig. 4). It incorporates the effects of temperature on the biasing magnet and the change in magnetization characteristics of the YIG film. The magnetization of the YIG film decreases with an increase in temperature until it reaches zero at the Curie point. The 14-μm film used has a Curie temperature of 552°C. From the manufacturer's curves for the magnet, the magnetic bias variation due to temperature should not exceed 2.5 percent over a range of $-50°$ to 80°C. The change in time delay characteristics shown in Fig. 4, therefore, can be mainly attributed to the change in saturation magnetization $4\pi Ms$ of the YIG film. One notices that the shift of the time delay versus frequency over temperature is very similar to the change due to varying magnetic bias field intensity. Thus, it should be possible to compensate for the change in temperature by changing the magnetic bias field accordingly. An analytical relation for the change in magnetic field ΔH required to compensate for the change in temperature ΔT at a given frequency ω_0 is

$$\Delta H = \frac{4\pi M_s \cdot C_{M_s}^T \cdot \Delta T\{2\Omega d \cdot \omega_m \cdot t_D e^{-2kd} - 8\Omega^2\}}{4(1+2\Omega_H)} \quad (4)$$

where

ΔT change in temperature from T to $(T+\Delta T)$
t_D (dk/dw) = time delay per unit length at temperature T
k propagation constant value at temperature T

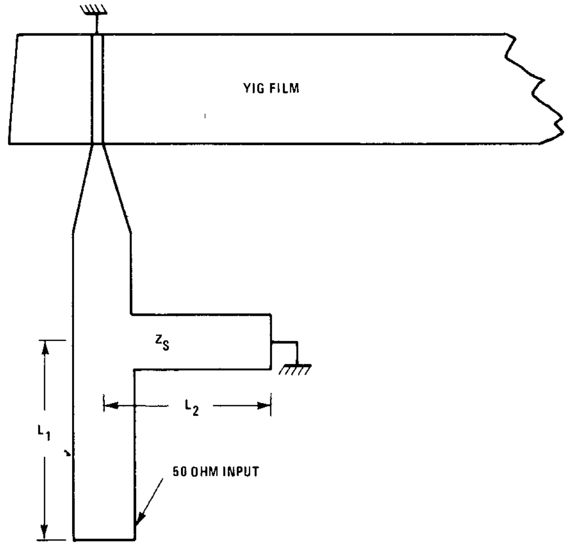

Fig. 1. Microwave matching network for YIG-film delay line

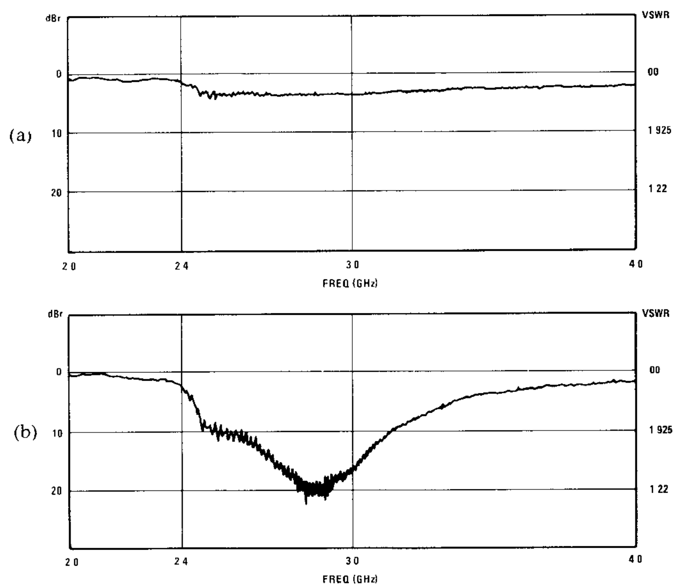

Fig. 2. Return loss improvements with microwave matching network. (a) Unmatched. (b) Matched

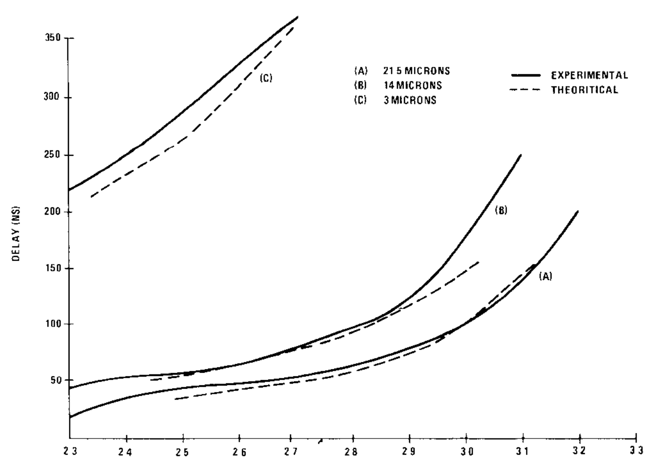

Fig 3. Effect of YIG-film thickness on time-delay and dispersion.

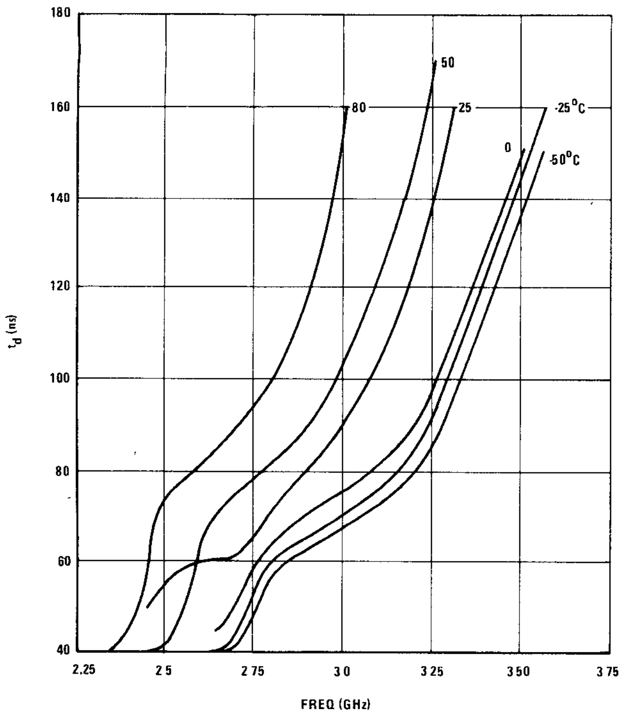

Fig. 4. Experimental results for temperature effects on time-delay characteristics.

$C^T_{M_s}$ thermal coefficient of the magnetization of the film
Ω ω_0/ω_m
Ω_H ω_c/ω_m
ω_c $2\pi\gamma H$ is the gyromagnetic angular frequency at external bias field H.
ω_m $2\pi\gamma \cdot 4\pi M_s$ is the angular frequency corresponding to saturation magnetization $4\pi M_s$ of the YIG.

Equation (4) is derived from the dispersion relation for MSSW localized at an unmetallized YIG surface.

IV. Dispersion Modification for Signal Processing

It has been recognized that the sophistication of many systems could be reduced if signal processing could be done directly in microwave frequencies. Some of the fundamental components would be highly dispersive, linearly dispersive and nondispersive, fixed and variable wide-band delay lines. Linearly dispersive delay lines are the key components in microscan receivers, pulse compression radars, and other advanced Fourier-transform techniques.

The dispersive characteristics of MSW can be substantially modified, thus enabling wide-band signal processing in microwave frequencies. MSW dispersion modification can be achieved by means of optimal ground planespacing, magnetic bias field intensity, and path modifications.

A single or multiple YIG film with an optimally placed ground plane represents the most commonly used technique for MSW dispersion modification. It has been experimentally verified for the MSFVW that a simple structure consisting of a YIG film spaced a distance equal to its thickness above a ground plane will give rise to a linear dispersion over 1-GHz bandwidths throughout the microwave region [8].

As well, the dispersive nature of MSW could be modified by path modification using specially designed oblique incidence reflective arrays. In concept, the nonrecursive transversal filter techniques at VHF/UHF achieved by means of surface acoustic wave (SAW) devices could be applied to MSW. It should be noted, however, that while the RAC-type configuration may be employed with MSFVW, the MSSW's and MSBVW's are not amenable to it. With the latter waves, an in-line normal-incidence reflective grating may be used. Metal fingers, metal dot arrays, and grooves can be used for implementation of the reflective grating elements. The metallic reflective elements could be fabricated on a dielectric layer sputtered on the YIG film. Spacing of the array elements from the YIG film will reduce the coupling, enabling each element to act as a weak reflector. This is a requirement for a transversal filter-type structure. This technique dramatically reduces the insertion loss of the device as well by lifting the array elements above the YIG film. Control of the dispersive characteristics can lead to another interesting application, where a linearized upchirp MSSW or MSFVW device can be cascaded with a downchirp MSBVW device for the purpose of dispersion minimization over wide bandwidths. Such variable, nondispersive delay lines find application in wide-band phased-array antennas. A unique feature of MSW delay lines is the ease with which they can be tuned over different frequencies by means of varying the magnetic field intensity. Experimental results indicate that the modified bandpass response could be tuned over several gigahertz without noticeable change of shape.

V. Summary

Dispersive characteristics of MSW devices were investigated. Relatively low propagation velocity promises SAW-like signal processing capabilities directly at microwave frequencies.

A highly dispersive delay line operating around 3 GHz was implemented and optimized for dispersion enhancement. The particular EW system application does not require dispersion linearization; however, ongoing work indicates the feasibility of dispersion modification by means of ground-plane spacing and planar arrays. Close agreement with theory indicates that LPE-grown YIG films have attained maturity and are usable at microwave frequencies. Temperature effects on YIG-film delay lines could be compensated by varying the magnetic bias field intensity.

It appears that continuous material research and circuit and array modeling in conjunction with computer optimization will enable the development of dispersive delay lines for a new family of signal processing components operating directly at microwave frequencies.

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