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Slow-Wave Characteristics of Ferromagnetic Semiconductor Microstrip Line*

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ABSTRACT

A new slow-wave microstrip line made of a ferromagnetic semiconductor (FMS) substrate is proposed and its characteristics discussed. It is shown that this structure has more desirable and flexible guided wave properties than the conventional metal-insulator-semiconductor (MIS) microstrip line.

INTRODUCTION

Recently, with the advance of monolithic microwave integrated circuit (MMIC) technology, it is recognized important for MMIC's to reduce the size of the passive circuits, because the passive components such as matching circuits and hybrid circuits require larger chip area than the active devices. One attempt to decrease the transmission-line length of MMIC's has been done by using the MIS structure [1]-[4], in which the slow-wave mode with its phase velocity as small as a few percent of the free spaced velocity can propagate. However, the slow-wave factor decreases with an increase of frequency, because the imaginary part of the permittivity needed for generation of the slow-wave mode is inversely proportional to the frequency. Another problem of the MIS microstrip line is its low characteristic impedance.

This paper proposes the FMS microstrip line as an alternative slow-wave transmission line. With an appropriate choice of the structural parameters, the slow-wave factor at high frequencies can be enhanced and the characteristic impedance adjusted in a practical level in the microstrip line created on an FMS such as $NiFe_2O_4$, $ZnFe_2O_4$ and $MnFe_2O_4$ [5][6]. The slow-wave mode in the FMS structure is produced by both the ferromagnetic and dielectric losses in the substrate. In contrast, an ordinary MIS slow-wave mode is generated by only the dielectric loss.

This paper first describes the possibility of the slow-wave mode on such a substrate. Second, some numerical results are shown and compared with the MIS microstrip line. The FMS microstrip line described here can increase the slow-wave factor larger than the MIS microstrip line. Therefore, it will extend the appliction area of the slow-wave transmission line to much higher frequencies. Although the beauty of MMIC's based on GaAs is no longer available, the new slow-wave configuration may find the application in conjunction with GaAs MMIC as such devices as delay line, phase shifter and directional coupler.

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SLOW-WAVE CHARACTERISTICS ON FERROMAGNETIC SEMICONDUCTOR SUBSTRATE

It is assumed that a quasi-TEM mode propagates in the transmission line being studied here. The fundamental aspect discussed below can be adapted to the hybrid microstrip line model. The equivalent circuit of the lossy distributed transmission line consists of the series inductance L, the series resistance R, the parallel capacitance C and the parallel conductance G. These components are determined by the complex permittivity and permeability of the substrate material and the dimension of the microstrip line. From the transmission line theory [7], the propagation constant $\gamma=\alpha+j\beta$ and the characteristic impedance $Zc=Rc + jXc$ are written as:

$$\gamma \simeq j\omega\sqrt{LC}\left[1-j\frac{1}{2}\left(\frac{R}{\omega L}+\frac{G}{\omega C}\right)\right] \quad (1)$$

$$Zc \simeq \sqrt{\frac{L}{C}}\left[1-j\frac{1}{2}\left(\frac{R}{\omega L}-\frac{G}{\omega C}\right)\right] \quad (2)$$

where α and β are the attenuation and phase constants, respectively, and ω is the angular frequency. From Eq.(1), the characteristics of the phase constant is mainly determined in the series inductance and the parallel capacitance. It has been reported in many papers that the slow-wave characteristics of the MIS microstrip line depend on the large capacitance effect between the microstrip and ground conductors [3]-[5]. In Fig. 1(a), while the electric energy is stored in the thin insulator layer, the magnetic energy is stored mainly in the semicondutor layer. It is conceivable that the phase constant can also be increased by the large inductance. This will be realized by using the lossy ferromagnetic substrate (Fig.1(b)). If the capacitance and the inductance can be increased at the same time, the slow-wave factor can be increased further (Fig.1(c)).

It is known that the characteristic impedance of the MIS microstrip line is low.

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This is because when the capacitance increases in Eq. (2), the characteristic impedance decreases. On the other hand, the characteristic impedance increases according to the increase of the inductance which occurs in the ferromagnetic substrate (Fig.1(b)). If the capacitance and the inductance increase simultaneously (Fig.1(c)), the characteristic impedance is not significantly affected in spite of the appearance of the slow-wave phenomena.

Table I summarizes the relation between the transmission characteristics and the substrate material. The ferromagnetic semiconductor substrate could have the possibility that the large slow-wave factor can be achieved at higher frequencies and the characteristic impedance can be in the practical range compared with other two substrates.

PARALLEL PLATE WAVEGUIDE MODEL

Since the primary objective of this paper is the study of the fundmental mechanism of qualitative characteristics, the parallel plate waveguide model has been used. A full wave analysis [4] can be easily adapted if more quantitative information is needed.

The fundamental propagation mode of the parallel plate waveguide is a TM mode [1]. The longitudinal (z-direction) propagation constant is characterized by the complex number $\gamma=\alpha+j\beta$. By using the transverse resonance method, the following equation is derived:

$$\gamma_i^2+\gamma^2=-\omega^2\varepsilon_i\mu_i, \Sigma\frac{\gamma_i}{j\omega\varepsilon_i}\tanh\gamma_i d_i=0 \quad i=1,2,\ldots n \qquad (3)$$

where γ_i denotes the transverse propagation constant in the y direction and i layer, d_i is the thickness of each layer, and $\varepsilon_i=\varepsilon_i'-j\varepsilon_i''$ and $\mu_i=\mu_i'-j\mu_i''$ denote the complex permittivity and permeability of each layer. The dispersion characteristics for the complex propagation constant are obtained from the eigenvalue solutions of Eq. (3) [8].

NUMERICAL RESULTS

The permeability of the ferromagnetic substrate is characterized by a tensor. Tensor elements depend on the ferromagnetic substrate material and the external magnetic field. In this paper, in order to make clear the fundamental slow-wave characteristics of the FMS microstrip lines, the demagnetized substrate is used as a lossy material, in which the off-diagonal tensor elements are equal to zero. The relative permeability is given as follows [9][10]:

$$\mu'=\frac{2}{3}\left[1-\left(\frac{\gamma 4\pi M_s}{\omega}\right)^2\right]^{\frac{1}{2}}+\frac{1}{3},\quad \mu''=A\left(\frac{\gamma 4\pi M_s}{\omega}\right)^N \qquad (4)$$

where γ is the gyromagnetic ratio and $4\pi M_s$ is the saturation magnetization, and A and N are parameters which depend on the substrate material.

The slow-wave characteristics of the FMS (Fig.1(c)) microstrip line are calculated by Eqs. (3) and (4). Figs. 2-5 show the frequency characteristics of the FMS microstrip line. Several values of A and N in Eq.(4) are selected in the calculation. The ferromagnetic substrate has another parameter of the conductivity which is a part of the permittivity. In these figures, the conductivity is fixed at $\sigma=10^3$. The dotted lines show the slow-wave characteristics of the MIS microstrip line for comparison. The frequency characteristics of the FM microstrip line are also calculated by Eqs. (3) and (4). These results show that the FM microstrip line can propagate the slow-wave mode as predicted. The results are not contained in this abstract due to space limitation, but will be included in the presentation.

CONCLUSION

The slow-wave characteristics of the FM and FMS microstrip lines have been predicted. The feature of the slow-wave transmission lines analyzed here is summarized.

(1) The great improvement of the slow-wave factor has been achieved by the FMS microstrip line (see Fig.2). Both the magnetic and dielectric loss contribute to the icrease of the slow-wave factor.

(2) The attenuation constant is greater than the MIS microstrip line at the lower frequency because the magnetic loss increases rapidly in the vicinity of the natural resonant frequency (see Fig. 3). On the other hand, if the magnetic loss is small, the loss depends on the dielectric loss at high frequencies.

(3) While the characteristic impedance of the FMS microstrip line is larger than that of the MIS microstrip line (see Figs. 4 and 5),it is much smaller than that of the FM microstrip line, though not shown in the figure. The FM microstrip line has a large characteristic impedance because of the increase of the series inductance. Hence, the characteristic impedance of the FMS microstrip line is in the practical range. This feature makes it easy to connect this structure with other circuit elements which has the 50-ohm input/output impedance.

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Table I Comparison of three slow-wave transmission lines

Transmission line	MIS microstrip line	FM microstrip line	FMS microstrip line
Cause of slow-wave	dielectric loss	magnetic loss	dielectric loss and magnetic loss
Slow-wave factor at higher frequency	small	small	large
Characteristic impedance	low	high	practical value in the middle range

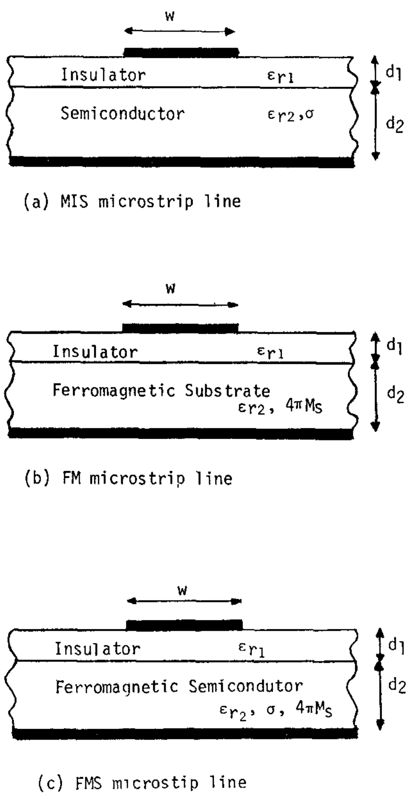

Fig. 1 Structures of slow-wave transmission lines

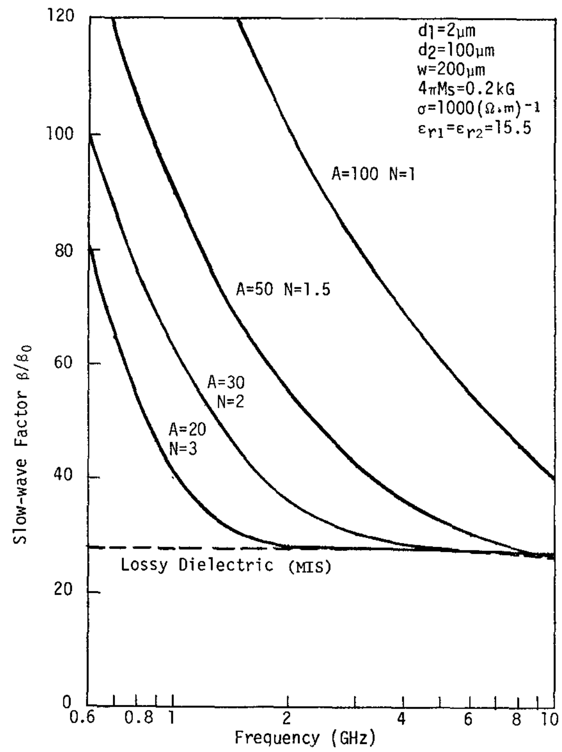

Fig. 2 Slow-wave factor vs. frequency

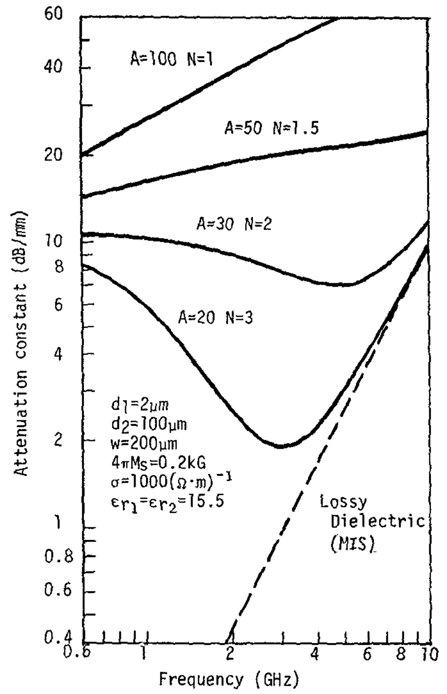

Fig. 3 Attenuation constant vs. frequency

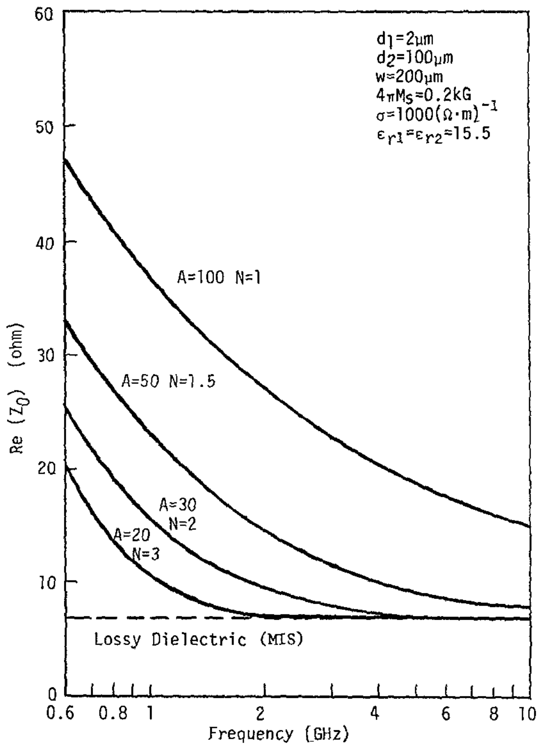

Fig. 4 $Re(Z_0)$ vs. frequency

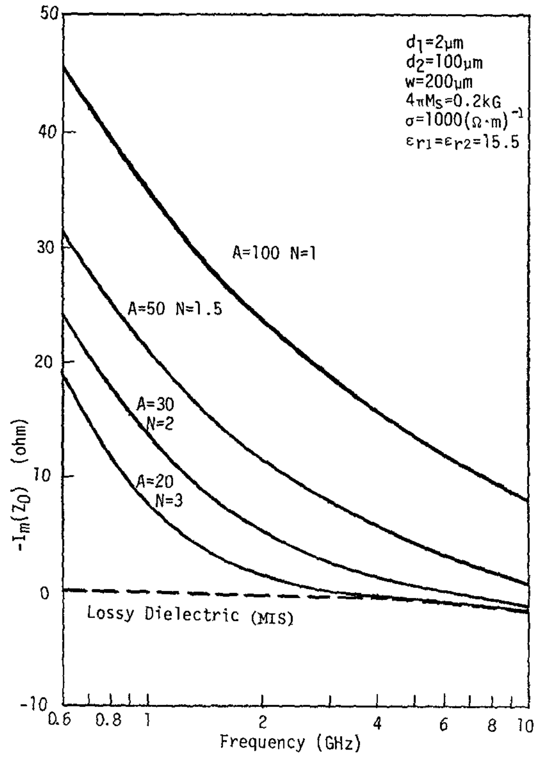

Fig. 5 $I_m(Z_0)$ vs. frequency