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 are discussed. Another possibility of a slow-wave microstrip line by a ferromagnetic (FM) substrate is also described in this paper. It is shown that these structures have more desirable and flexible guided wave properties than the conventional metal–insulator–semiconductor (MIS) microstrip line.**

I. Introduction

RECENTLY, with the advance of monolithic microwave integrated circuit (MMIC) technology, it is considered important that MMIC's reduce the size of the passive circuits, because 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 made by using the MIS structure (Fig. 1(a)) [1]–[4], in which the slow-wave mode with its phase velocity as small as a few percent of the free-space velocity can propagate. However, the slow-wave factor decreases with an increase of frequency, because the imaginary part of the permittivity needed for spatial separation of the electric and magnetic energy storage is inversely proportional to the frequency ($\epsilon'' = \sigma/\omega\epsilon_0$). Another problem of the MIS microstrip line is its low characteristic impedance. Some attempts have been reported in which the slow-wave phenomena are created by the spatial separation of energy storage by means of a periodic structure [5], [6].

This paper proposes the ferromagnetic semiconductor (FMS) and ferromagnetic (FM) microstrip line as an alternative slow-wave transmission line. In the FM structure (Fig. 1(b)), an appropriate ferromagnetic loss causes spatial separation of electric and magnetic energy. Hence, a large series inductance is generated while the line capacitance is little affected. This structure is essentially a dual of the MIS slow-wave configuration. Note that if a lossless ferromagnetic substrate is used, the phase velocity decreases but the slow-wave factor is not as large as the one in an FM structure. The relation between the structures with a lossy and a lossless magnetic material is analogous to that of an MIS and a microstrip on a lossless, high-permittivity dielectric substrate. The slow-wave mode in the FMS structure (Fig. 1(c)) is produced by two types of spatial energy separation, one resulting from the ferromagnetic loss and the other from dielectric loss in the substrate. In contrast, in an ordinary MIS slow-wave mode, the spatial separation is generated by only the dielectric loss. With an appropriate choice of 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 substrate such as $NiFe_2O_4$, $ZnFe_2O_4$, and $MnFe_2O_4$ [7], [8].

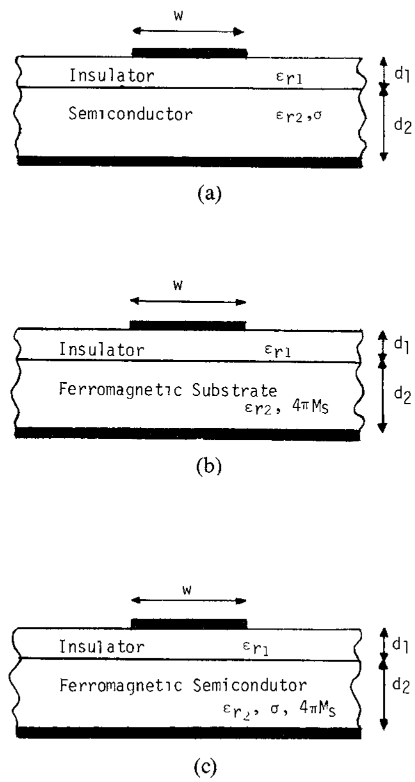

Fig. 1. Structures of slow-wave transmission lines. (a) MIS microstrip line. (b) FM microstrip line. (c) FMS microstrip line.

This paper first describes the possibility of the slow-wave mode on such substrates. 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 to a value larger than that of the MIS microstrip line. Therefore, it will extend the application area of the slow-wave transmission line to much higher frequencies. Although the new structures cannot be built

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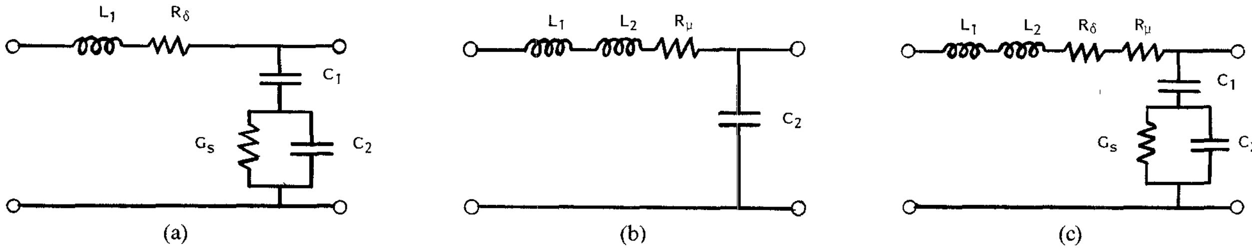

Fig. 2. Equivalent circuits of slow-wave transmission lines. (a) MIS microstrip line. (b) FM microstrip line. (c) FMS microstrip line.

TABLE I
COMPARISON OF THREE SLOW-WAVE TRANSMISSION LINES

Transmission line	MIS microstrip line	FM microstrip line	FMS microstrip line
Cause of slow-wave	Large capacitance and dielectric loss	Large inductance and magnetic loss	Both large capacitance and inductance, and both dielectric loss and magnetic loss
Slow-wave factor at higher frequency	Small	Small	Large
Characteristic impedance	Low	High	Practical value in the medium range

on a GaAs substrate, the new slow-wave configuration may find applications in conjunction with GaAs MMIC's as delay lines and directional couplers.

II. Slow-Wave Characteristics on Ferromagnetic Semiconductor Substrate

Since the primary objective of the paper is to study the fundamental mechanism of qualitative characteristics, a parallel-plate waveguide model is used for analysis and a TM mode propagation is assumed. In an actual microstrip line with a finite strip width, the modal field is hybrid. The essential feature reported in this paper will be incorporated through the TM part of the hybrid field. A more rigorous analysis technique such as the spectral-domain method can be used for FM and FMS microstrip configurations.

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 [1]–[4]. Fig. 2(a) displays an equivalent circuit for an MIS slow-wave line [1]. While the electric energy is stored in the thin insulator layer (C_1), the magnetic energy (represented by L_1) is stored mainly in the semiconductor layer. It is conceivable that the phase constant can also be increased by the large inductance (L_2) in an FM configuration due to spatial separation of energy by the use of a lossy ferromagnetic substrate (Fig. 2(b)). If the capacitance (C_1) and the inductance (L_2) can be increased at the same time, the slow-wave factor can be increased further (Fig. 2(c)). In Fig. 2, R_δ, G_s, C_2, and R_μ correspond to the skin depth resistance, the semiconductor bulk conductance, the thick-layer capacitance, and the ferromagnetic loss resistance, respectively.

It is known that the characteristic impedance of the MIS microstrip line is low. This is because when the capacitance is increased, the characteristic impedance decreases. On the other hand, the characteristic impedance can be increased if the inductance is increased in the FM structure (Fig. 2(b)). If the capacitance and the inductance are increased simultaneously (Fig. 2(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 the other two substrates.

III. Parallel-Plate Waveguide Model

As stated earlier, the primary objective of this paper is the study of the fundamental mechanism of qualitative characteristics. A parallel-plate waveguide model is convenient for this purpose. A full-wave analysis [4] can be easily adapted if more quantitative information such as the effect of finite width of the microstrip line 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 equations are derived:

$$\gamma_i^2 + \gamma^2 = -\omega^2 \epsilon_0 \mu_0 \epsilon_i \mu_i, \qquad i = 1, 2 \tag{1}$$

$$\sum_{i=1}^{2} \frac{\gamma_i}{j\omega\epsilon_0\epsilon_i} \tanh \gamma_i d_i = 0 \tag{2}$$

where γ_i denotes the transverse propagation constant in the y direction and i layer, d_i is the thickness of each layer, and $\epsilon_i = \epsilon_i' - j\epsilon_i''$ and $\mu_i = \mu_i' - j\mu_i''$ denote the complex permittivity and permeability of each layer. The dis-

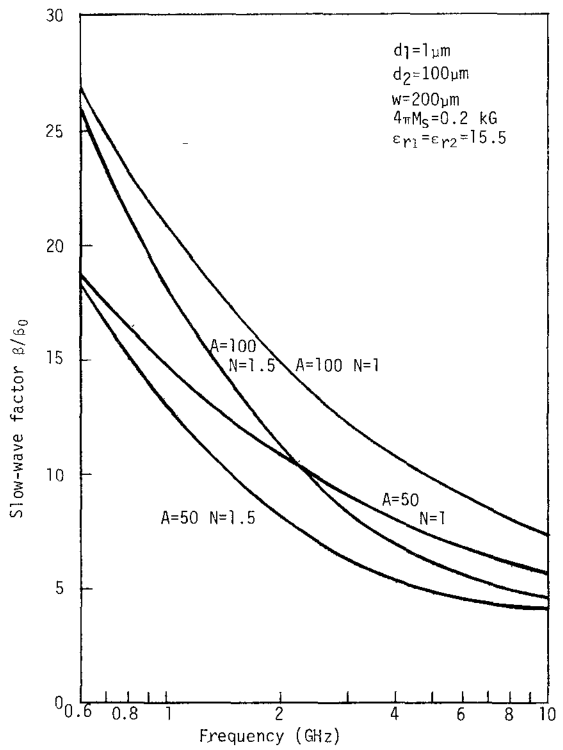

Fig. 3. Slow-wave factor of FM microstrip line versus frequency.

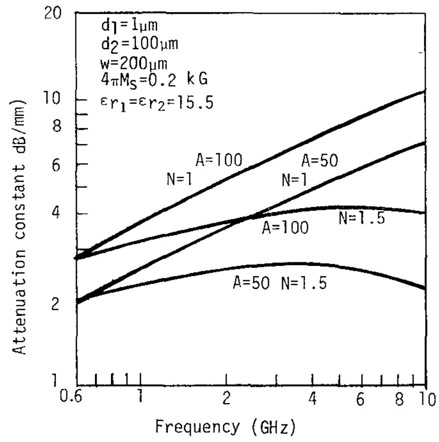

Fig. 4. Attenuation constant of FM microstrip line versus frequency.

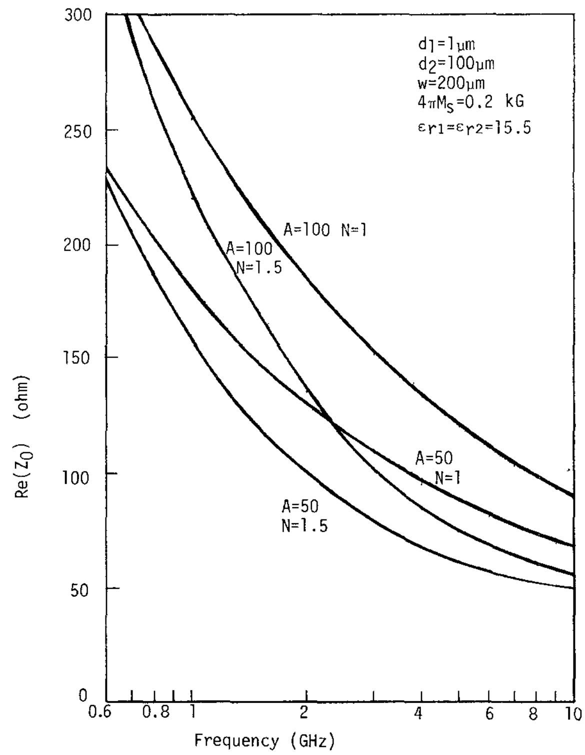

Fig. 5. Real part of characteristic impedance of FM microstrip line versus frequency.

persion characteristics for the complex propagation constant are obtained from the eigenvalue solutions of (3) and (4) [9], [10].

IV. 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 FM and 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 [11], [12]:

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

$$\mu'' = A\left(\frac{\gamma 4\pi M_s}{\omega}\right)^N \qquad (4)$$

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

The frequency characteristics of the FM microstrip line are shown in Figs. 3–6. Under the present parallel-plate assumption, the characteristic impedance is the ratio of the series impedance to the shunt admittance of the equivalent transmission line [1], [3]. These results show that the slow-wave factor can propagate on the FM microstrip line as predicted. The ferrite is selected as the substrate material. Several values of A and N in (6) are selected in the calculation.

The slow-wave characteristics of the FMS (Fig. 1(c)) microstrip line are calculated by (3)–(6). Figs. 7–10 show the frequency characteristics of the FMS microstrip line. Several values of A and N 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 $\sigma = 10^3$ $(\Omega \cdot \mathrm{m})^{-1}$. The dotted lines show the slow-wave characteristics of the MIS microstrip line whose semiconductor substrate has a conductivity of 10^3 for comparison.

V. Conclusions

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

1) The slow-wave mode can propagate on the FM microstrip line (see Fig. 3). The slow-wave factor decreases as

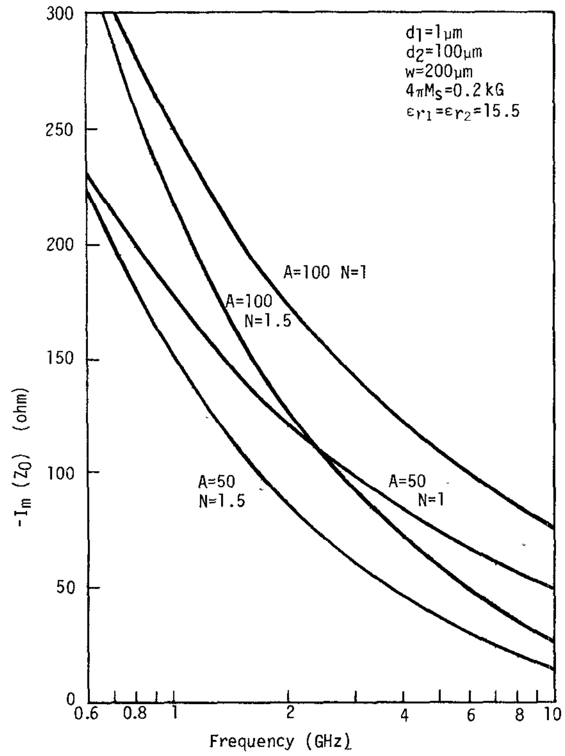

Fig. 6. Imaginary part of characteristic impedance of FM microstrip line versus frequency.

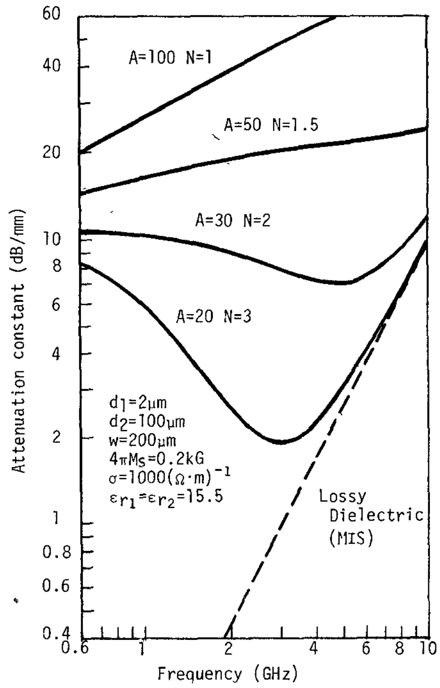

Fig. 8. Attenuation constant of FMS microstrip line versus frequency. The dotted line shows the attenuation constant of MIS microstrip line.

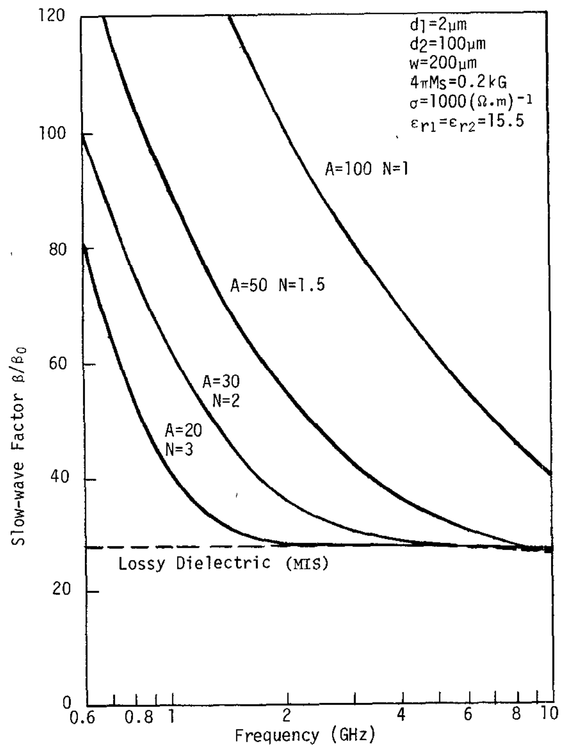

Fig. 7. Slow-wave factor of FMS microstrip line versus frequency. The dotted line shows the slow-wave factor of MIS microstrip line.

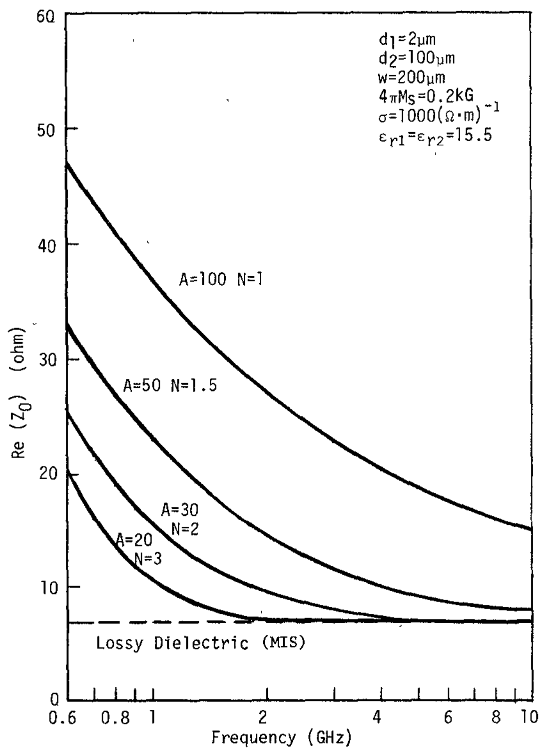

Fig. 9. Real part of characteristic impedance of FMS microstrip line versus frequency. The dotted line shows the real part of characteristic impedance of MIS microstrip line.

the frequency increases, because the ferromagnetic substrate has a large loss near the natural resonant frequency (see Fig. 4).

2) The FM microstrip line has a large characteristic impedance because of the increase of the series inductance (see Figs. 5–6). The reason why the characteristic impedance decreases as the frequency increases is the frequency dependence of the permeability.

3) The great improvement of the slow-wave factor has been achieved by the FMS microstrip line (see Fig. 7). Both the magnetic and the dielectric loss contribute to the increase of the slow-wave factor.

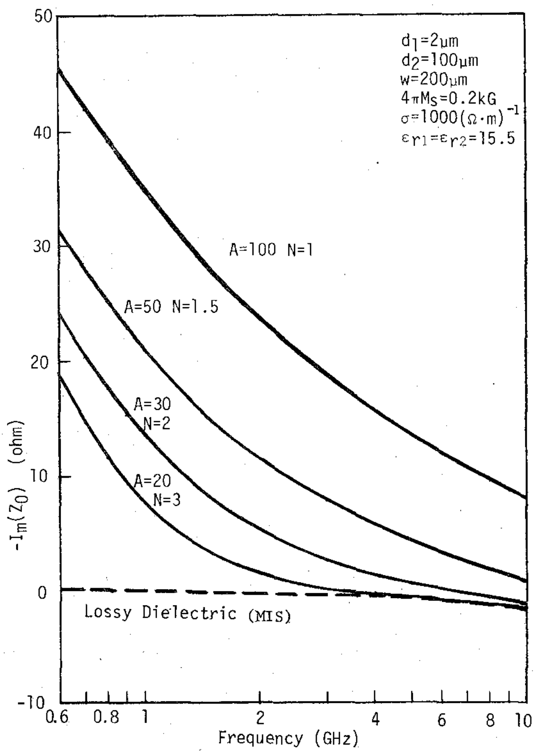

Fig. 10. Imaginary part of characteristic impedance of FMS microstrip line versus frequency. The dotted line shows the imaginary part of characteristic impedance of MIS microstrip line.

4) 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. 8). On the other hand, if the magnetic loss is small, the loss depends on the dielectric loss at high frequencies.

5) The FMS microstrip line has a larger attenuation loss than both MIS and FM microstrip lines. The improvement of the slow-wave factor and the characteristic impedance is obtained at the sacrifice of increased loss. This is definitely a limiting factor for applications. However, the structure can find practical use in several important areas such as the attenuation circuit with a small size and a well-matched impedance [13].

6) While the characteristic impedance of the FMS microstrip line is larger than that of the MIS microstrip line (see Figs. 9 and 10), it is much smaller than that of the FM microstrip line, though not shown in the figure. 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 have the 50-Ω input/output impedance.

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