Slow-Wave Propagation of Microstrip Consisting of Electric-Magnetic-Electric (EME) Composite Metal Strips

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***Abstract* — A novel integrated microstrip slow-wave line is presented. The new microstrip replaces the conventional metal strip by the composite metals paralleling the electric and magnetic surfaces. The magnetic surface is made of an array of coupled inductors that perturb the modal currents periodically. The theoretical results, validated by experiment, show that more than 60% increase in the slow-wave factor while maintaining the Q-factor values can be achieved using the proposed structure.**

I. Introduction

Wave propagation in a microstrip experiencing periodic perturbations has shown great potential for a great variety of applications in microwave electronics and antenna development. Microstrip with twenty to more than one hundred percent increase in the slow-wave factor, while simultaneously maintaining nearly the same characteristic impedance, has been demonstrated using a genuine periodical structure named UC-PBG placed under the microstrip [1]. Power amplifier of efficiency greater than sixty percent was reported by incorporating the inherent stopband characteristics of such periodical microstrip structure [2]. Increasing new applications using the above-mentioned microstrip technology and its variants are constantly reported, for examples [3, 4].

This paper presents a novel slow-wave line implemented by adding a periodical structure alongside the metal strip(s) in the axial direction as shown in Fig.1. It is like a conventional microstrip sitting on a continuous, uniform ground plane except the metal strip is now a composite metal made of the electric-magnetic-electric surfaces. The electrical surface is an ordinary metal strip of certain thickness. A number of coupled, connected metallic coils realize the magnetic surface. These coils form a periodic array at the central plane of the microstrip. The principle and operation of the proposed magnetic surface behaves in a similar way to what have been reported for various high-impedance-surface designs [5, 6]. The proposed guiding structure is symmetrical about the central plane, which is a magnetic (electric) wall for the even- (odd-) mode operation. Notice that the magnetic surface is frequency-dependent, implying that the impedance of the magnetic surface is high enough at certain frequency band. In view of the frequency-dependent magnetic surface at the central plane, the odd-mode dispersion characteristics will be changed accordingly. This paper, however, will focus on the even-mode propagation that shows advantageous applications when increased slow-wave factor, higher characteristic impedance, and high Q-factor of a microstrip line is desired.

Section II describes the design of the electric-magnetic-electric (EME) microstrip and reports the corresponding scattering analyses, which are compared and validated by measurement. Section III reports the extracted values of the propagation constants and characteristic impedances derived from the scattering analyses of various microstrip structures, demonstrating the generality of using the EME microstrip configuration. Two theoretical methods are employed to confirm the validity of the reported transmission line data. The loss assessment of the proposed EME microstrip is briefly discussed in Section IV. Section V concludes the paper.

II. EME (Electric-Magnetic-Electric) Microstrip Design and Validity Check

A. EME Microstrip

From left to right, replacing the top metal layer of the classic microstrip structure by the composite metal formed by paralleling 1) metal strip, 2) periodical structure and 3) metal strip as seen in Fig. 1, a novel slow-wave line is devised. The periodical structure is designed to show a stopband around a desired frequency, which is much higher than the normal operating frequency when the microstrip bound mode is in need. In the stopband the periodical structure turns into a high-impedance state, commonly known as a magnetic surface. In the particular design presented here, the first stopband of the periodical structure is designed at 10 GHz with cells size of 2.25 mm by 2.25 mm. The periodical structure consists of an array of coils, which are essentially coupled spiral inductors as illustrated in Fig. 1. The presence of the magnetic surface alters the modal current distributions along the transverse and longitudinal directions of the guide, thereby changing the dispersion characteristics of the microstrip. By varying the widths W_E and W_M of the EME (electric-magnetic-electric) microstrip, we may adjust the propagation constant and the characteristic impedance of the transmission line. The EME microstrip line is compatible with modern state-of-the-art multilayered printed circuit technology. To this end the microstrip with EME surfaces is investigated. To demonstrate the potential application of the EME microstrip as a slow-wave line, the electric and magnetic surfaces are made on a two-sided printed RO4003^{TM} circuit board of 0.20 mm thickness (h_2) and relative dielectric constant ε_{r2} equal to 3.38, which is then glued to the grounded RO4003^{TM} substrate of thickness (h_1) 0.508 mm (see Fig. 1).

B. Validity Checks

A 15-cell long EME microstrip prototype of W_E= 0 mm and W_M= 2.25 mm, that is one period in the transverse direction, was built and tested. The EME microstrip becomes a magnetic-surface (MS) microstrip with 100 % periodical structure filling the metal strip. The reduced MS microstrip structure allows quick laboratory evaluation of the proposed concept. The magnetic surface was built by applying an engraving machine followed by via through-hole plating. First we compare the measured two-port scattering-parameters of the MS microstrip against those obtained by the full-wave integral equation method that assumes substrates of infinite extent. Fig. 2 plots the comparative results for S_{11} and S_{21}, showing good agreement between the theoretical and measured data. The measured scattering parameters are somewhat consistently shifted to right by approximately 0.95 GHz. Careful examination on the prototype indicates the engraving machine trims more metals than required, resulting in decrease in coupled capacitance between cells and thus moving the stopband toward higher frequency. The theoretical results show that the stopband is between 8.25 GHz and 11.25 GHz, centered at 9.75 GHz. Inside this stopband, the reflection coefficient is nearly one (0.95) with phase of 0 degree, showing the existence of an extremely high impedance state. When operating in the lower frequency region, the MS microstrip displays very good transmission characteristics with low reflection, although it is not exactly matched to the measurement system of 50 Ω impedance.

Next we invoke the matrix-pencil analyses of the ground returned currents of the MS microstrip to extract the dispersion characteristics of the space harmonics associated with the MS microstrip [7,8]. The presence of the periodical structure made of the coupled coils modulates the modal currents. Therefore the space harmonics will be present in the MS microstrip [7, 8]. In the low frequency region below 7.0 GHz, we find that the forward traveling wave and the backward traveling wave in the form of microstrip EH_0 mode are the two major components. Both traveling waves have the same phase constant but in opposite sign. Fig. 3 plots the phase constant of the dominant forward traveling wave component for the entire spectrum of interest. A bump appears at 8.0 GHz near the lower frequency corner of the stopband. Furthermore in the lower frequency region where the EH_0 mode of propagation dominates, we may directly extract the complex propagation constants and characteristic impedances from the scattering parameters. The results are superimposed to the existing curve for comparison. We also compare the dispersion curves of a uniform microstrip of equal dimensions and material constants. The results show that the dispersion curves obtained by the matrix-pencil analyses and S-parameters extraction are in excellent agreement. The physical explanation of the bump will be briefly discussed in Section IV. The increase in the slow-wave factor by 50 % in the low frequency limit of interest suggests that the proposed EME or MS microstrip incorporating the magnetic surface alongside the signal path is a viable concept for designing a slow-wave line.

III. CASE STUDIES: EME MICROSTRIP

Theoretical results for the slow-wave propagation of the microstrip incorporating the EME surfaces are presented. Simulations are carried out for microstrip with 0 %, 50 % and 100 % magnetic surface filling the metal strip of width 4.5 mm. Each unit cell that constitutes the periodical array is 2.25 mm by 2.25 mm, the same design reported in Section II. Furthermore the same RO4003^{TM} substrate of 0.508 mm thickness is employed for making the microstrip. First we initiate the numerical experiments by analyzing the conventional microstrip, followed by replacing the central portions of the metal strip by inserting the arrays of 1 by 15 and 2 by 15 cells, respectively. EME microstrip of 100 % magnetic surface filling is identical to the MS microstrip. Next we compare the slow-wave factor ($\lambda_0/\lambda g$) and the characteristic impedance of the EME line against the conventional microstrip.

Fig. 4 shows the comparative results for the EME microstrip of 50 % magnetic surface filling. The slow-wave factor (SWF) of the EME microstrip is flat until the operating frequency approaches the lower corner of the stopband frequency as discussed in Section II. The conventional microstrip shows SWF of 1.736 at 5 GHz, whereas the EME microstrip increases the SWF to 2.12 by 22 %. Furthermore the characteristic impedances of the conventional and EME microstrips are plotted. Unlike the microstrip on the UC-PBG surface [1], the characteristic impedance of the EME microstrip increases by 29 % as compared to the conventional one. This implies that the magnetic surface that partially occupies the metal strip does increase the distributed inductance per unit length, thereby increasing the SWF and characteristic impedance simultaneously.

The physical observations implied in Fig. 4 suggest that further increase in the percentage of magnetic surface filling should increase the SWF and characteristic impedance simultaneously. Fig. 5 proves this conjecture. The 100 % magnetic surface MS microstrip shows nearly 60 % increase in the SWF and 38 % increase in the characteristic impedance at 5 GHz. The increase in the distributed inductance per unit length as seen for the EME microstrips in Fig. 4 and Fig. 5 is clearly contributed by the magnetic surface.

IV. DISCUSSIONS: Q-FACTOR AND HIGHER ORDER EFFECTS

The loss assessment of the EME microstrip is divided into two categories, the low-frequency region suitable for slow-wave propagation and the high-frequency region near and above the lower corner frequency of the stopband. At the higher frequencies the EME microstrip no longer holds single mode operation, instead many space harmonics come into play as observed in the matrix-pencil analyses. We found strong radiations in the form of surface waves and space waves that occur near the lower corner frequency of the stopband. In the stopband some space harmonics enter the leaky wave region and surprisingly show little radiation. Therefore when a low-loss slow-wave line is desired, one should avoid using the EME microstrip near or above the lower corner frequency of the stopband. Analyzing the scattering parameters up to 5 GHz for the EME microstrip of 100 % magnetic surface filling, we find that the loss per guided wavelength of the EME microstrip is nearly the same as that of the corresponding conventional microstrip. Therefore we may increase the slow-wave factor and maintain the Q-factor if we operate the EME microstrip at the low-frequency region.

V. CONCLUSION

The concept of applying the periodical perturbations to enhance the slow-wave propagation of the most widely used microstrip lines as proposed by Itoh et al. [1] is further confirmed by the newly developed EME microstrip structure. A novel magnetic surface made of an array of coupled inductors shows a high-impedance state in the stopband, below which the slow-wave factor of the EME microstrip exhibits high controllability of the slow-wave factor by varying the percentage of magnetic surface filling the microstrip. A design example demonstrates 60 % increase in the slow-wave factor without sacrificing propagation losses.

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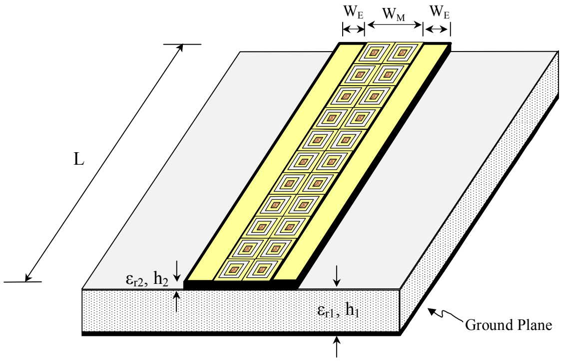

Fig. 1. Three-dimensional view of the proposed microstrip line with metal strip replaced by electric-magnetic-electric (EME) surfaces.

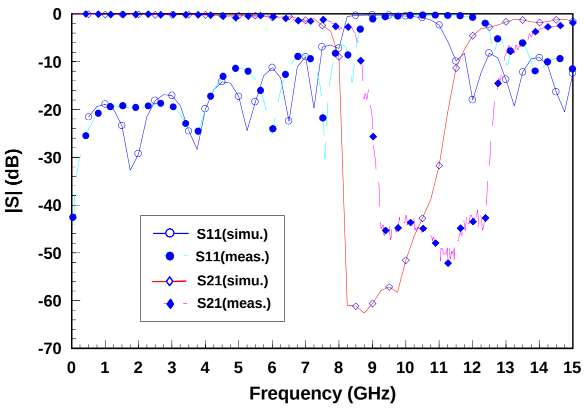

Fig. 2. Measured and computed scattering parameters for an EME microstrip with 100 % periodical structure filling, i.e., MS (magnetic surface) microstrip.

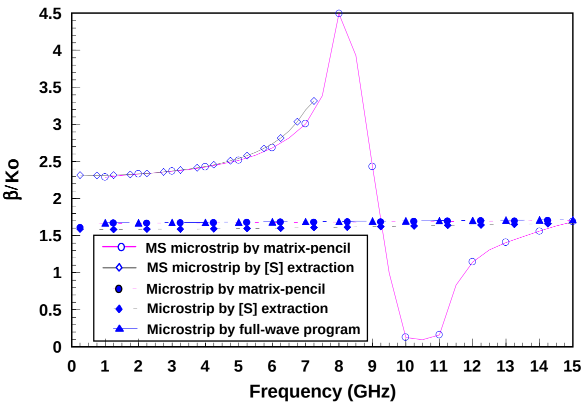

Fig. 3. Comparison of the slow-wave factor (SWF) of the MS microstrip and uniform microstrip, 50 % increase in SWF is shown by the proposed microstrip structure.

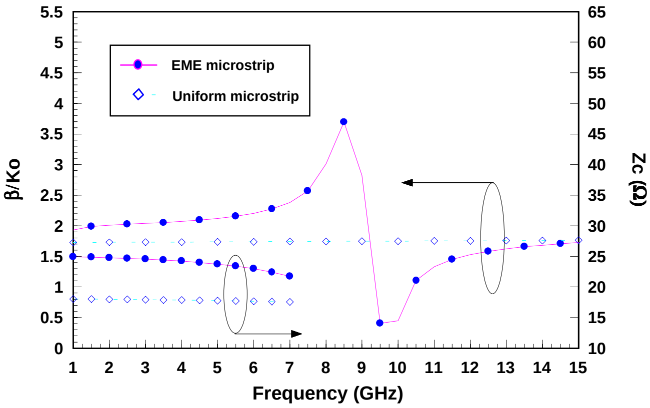

Fig. 4. Slow-wave factor and characteristic impedance of the EME microstrip of 50 % filling in comparison with the uniform microstrip.

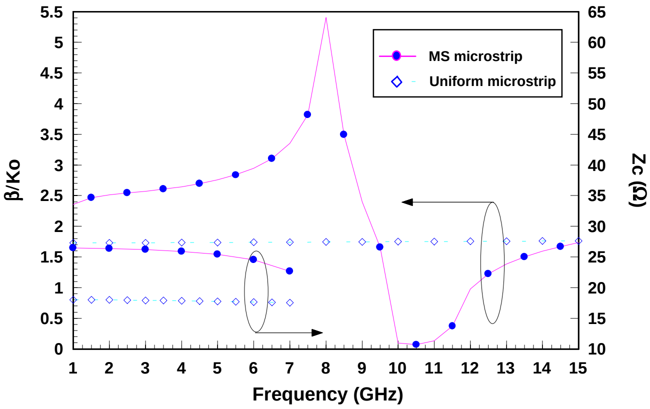

Fig. 5. Slow-wave factor and characteristic impedance of the MS microstrip (or EME microstrip of 100 % filling) in comparison with the uniform microstrip.