New Multilayer Planar Transmission Lines for Microwave and Millimeter-Wave Integrated Circuits

Pang-Cheng Hsu and Cam Nguyen

Abstract— **New types of planar transmission lines employing multilayer structures are proposed for possible applications in microwave and millimeter-wave integrated circuits. Detailed investigations are presented through numerical results calculated using the spectral domain technique. The newly proposed transmission lines have many attractive features such as a large impedance range, flexibility and ability to realize complicated, densely packed integrated circuits, as well as miniaturization through the use of thin dielectric layers. Additionally, they possess all of the inherent advantages of the CPW and microstrip line. Their use in microwave circuits is exemplified through a low-pass filter realized using the new slot-coplanar lines with less than 0.5-dB insertion loss and better than 20-dB return loss. The filter's measured and calculated performances also agree well.**

I. Introduction

MICROWAVE and millimeter-wave integrated-circuit technology, both hybrid (MIC) and monolithic (MMIC), has advanced considerably in the past decade. In the last few years, the trend of development has been toward multichip and multifunction MMIC modules, which contain many functions and high levels of complexity within a single package. The impetus of this development is to achieve low cost, miniaturization, and high performance. This effort is receiving even more attention as commercial applications of microwave technology, such as wireless communications, are becoming increasingly important. Crucial to this success are the creation and effective use of planar transmission lines that not only can miniaturize the sizes of circuits but also enhance their performances. Toward this purpose, the conventional microstrip line and coplanar waveguide (CPW) [1] play an important role, from which many planar transmission lines have evolved. Excellent candidates for achieving the characteristics of miniaturization, low weight, low cost, and high performance sought for MIC's and MMIC's are multilayer transmission lines. These transmission lines have the flexibility to realize complicated circuits, ultimately allowing very compact, high-density circuit integration. The use of thin dielectric layers can further reduce circuit size by achieving narrow line widths [2]–[7].

In this paper we propose and study several new planar transmission lines utilizing multilayer structures for possible applications in microwave and millimeter-wave integrated circuits. The transmission lines, as shown in Fig. 1, are compatible with both MIC and MMIC implementations. They can be classified into three different classes: slot-coplanar lines, consisting of double [Fig. 1(a)] and single [Fig. 1(b)] coplanar grounds, micro-slot line [Fig. 1(c)], and micro-coplanar lines comprised of double [Fig. 1(d)] and single [Fig. 1(e)] coplanar grounds. Their open versions are obtained by removing the enclosures as illustrated for one structure in Fig. 1(f). The proposed transmission lines are completely general, in which the strip, grounds, and slots can be arbitrarily located, a feature that is attractive toward realizing compact, high-performance, complex MIC's and MMIC's. Also, a bottom ground plane is used in all of the structures to increase mechanical strength as well as to facilitate heat sinking and packaging needed for practical applications. Symmetrical versions of the micro-slot line, in which the underside slot is aligned at the center of the strip, have been proposed and used, e.g., [3], [8]. Although a wider impedance range than that of the conventional microstrip line and CPW can be obtained, the symmetrically located slot limits the optimum achievable impedance range as well as the flexibility of the transmission line in circuit design. The newly proposed transmission lines are evolutions of the conventional microstrip line and CPW and, thus, maintain all the features of the microstrip and CPW. However, they exploit the advantages of multilayer structures as well as the couplings between the constituent strips and slots to improve the performance. These transmission lines have wider characteristic-impedance ranges than those of the conventional microstrip line and CPW. In addition, they have several desirable features such as flexibility and the ability to realize complicated, highly dense circuits through appropriate arrangements of the structural elements. Furthermore, the proposed structures allow thin dielectric layers to be deposited on conductor-backed GaAs semi-insulating substrate for achieving ultra-compact MMIC's. It is also expected that they have significantly less interline coupling, cross talk and distortion via appropriate selection of dielectric layers, as interestingly seen in multilayer microstrip lines [9], a fact making them even more attractive. Work along this line is being pursued using a full-wave analysis. Detailed investigations of the transmission lines are presented based on the spectral domain technique [10].

To demonstrate possible applications of the proposed transmission lines for MIC's and MMIC's and validate their analysis, we have also designed, built and tested a 4-GHz low-pass filter using the slot-coplanar lines. Its measured and calculated performances are presented here. As compared to low-pass filters employing the conventional CPW or microstrip line, this new slot-coplanar filter can have a higher selectivity due to a larger high/low characteristic-impedance ratio realized by simultaneously optimizing the strip and slots.

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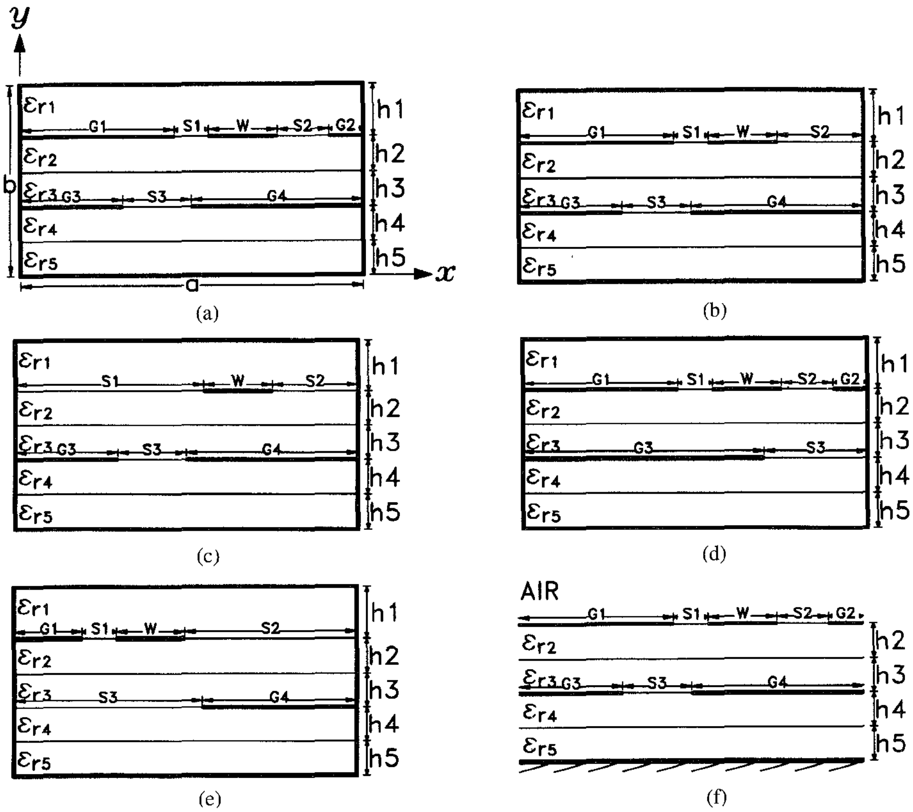

Fig. 1. Cross sections of the new multilayer planar transmissionlines: (a), (b) slot-coplanar lines; (c) micro-slot line; (d), (e) micro-coplanar lines; and (f) open version of (a).

II. Analysis

Fig. 1 shows the cross sections of the new multilayer planar transmission lines. They will be analyzed using the structure shown in Fig. 1(a), which is assumed to be uniform and infinite in the z-direction with a perfectly conducting enclosure. All the strips are assumed to be perfect conductors of zero thickness, and the dielectric substrates are assumed to be lossless. The enclosure is used to simplify some of the analysis and computation. The open structures, such as Fig. 1(f), can be accommodated by setting appropriate values to the structural parameters.

Applying the spectral domain method [10] yields the following coupled linear equations

$$\sum_{k=1}^{M}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{sj}\tilde{G}_{11}\tilde{\rho}_{sk}\right)c_k+\sum_{k=1}^{N_1}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{sj}\tilde{G}_{11}\tilde{\rho}_{G1k}\right)d_{1k}$$
$$+\sum_{k=1}^{N_2}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{sj}\tilde{G}_{11}\tilde{\rho}_{G2k}\right)d_{2k}$$
$$+\sum_{k=1}^{N_3}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{sj}\tilde{G}_{12}\tilde{\rho}_{G3k}\right)d_{3k}$$
$$+\sum_{k=1}^{N_4}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{sj}\tilde{G}_{12}\tilde{\rho}_{G4k}\right)d_{4k}=\frac{2V}{a}\int_{G1+S1}^{G1+S1+W}\rho_{sj}(x)\cdot dx j=1,2,\ldots,M$$

$$\sum_{k=1}^{M}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{11}\tilde{\rho}_{sk}\right)c_k+\sum_{k=1}^{N_1}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{11}\tilde{\rho}_{G1k}\right)d_{1k}$$
$$+\sum_{k=1}^{N_2}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{11}\tilde{\rho}_{G2k}\right)d_{2k}$$
$$+\sum_{k=1}^{N_3}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{12}\tilde{\rho}_{G3k}\right)d_{3k}$$
$$+\sum_{k=1}^{N_4}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{12}\tilde{\rho}_{G4k}\right)d_{4k}=0$$
$$j=1,2,\ldots,N_i \text{ and } i=1,2$$

$$\sum_{k=1}^{M}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{12}\tilde{\rho}_{sk}\right)c_k+\sum_{k=1}^{N_1}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{12}\tilde{\rho}_{G1k}\right)d_{1k}$$
$$+\sum_{k=1}^{N_2}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{12}\tilde{\rho}_{G2k}\right)d_{2k}$$
$$+\sum_{k=1}^{N_3}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{22}\tilde{\rho}_{G3k}\right)d_{3k}$$
$$+\sum_{k=1}^{N_4}\left(\sum_{n=1}^{\infty}\tilde{\rho}_{Gij}\tilde{G}_{22}\tilde{\rho}_{G4k}\right)d_{4k}=0$$
$$j=1,2,\ldots,N_i \text{ and } i=3,4$$

where $\tilde{\rho}$'s are basis functions representing the charge densities of the strip and ground planes in the spectral domain; c's and d's are unknown expansion coefficients; V is the potential

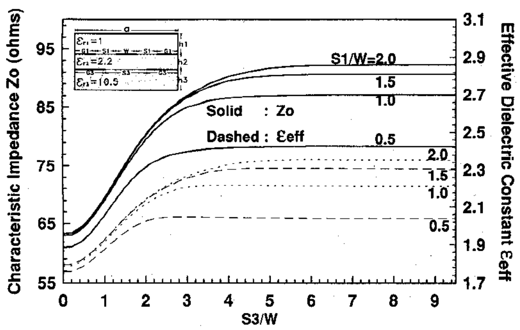

Fig. 2. Characteristic impedance and effective dielectric constant of a symmetric slot-coplanar line versus the lower-slot width. $a = 5h_1 = 20h_2 = 5h_3 = 10\text{W} = 100$ mils; $\varepsilon_{r1} = 1$; $\varepsilon_{r2} = 2.2$; $\varepsilon_{r3} = 10.5$.

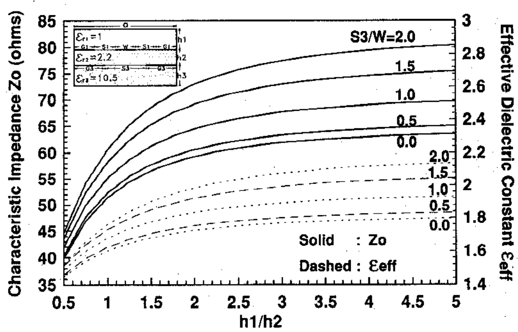

Fig. 3. Characteristic impedance and effective dielectric constant of a symmetric slot-coplanar line versus the height of the upper layer. $a = 20h_2 = 5h_3 = 10\text{W} = 10\text{S}_1 = 100$ mils; $\varepsilon_{r1} = 1$; $\varepsilon_{r2} = 2.2$; $\varepsilon_{r3} = 10.5$.

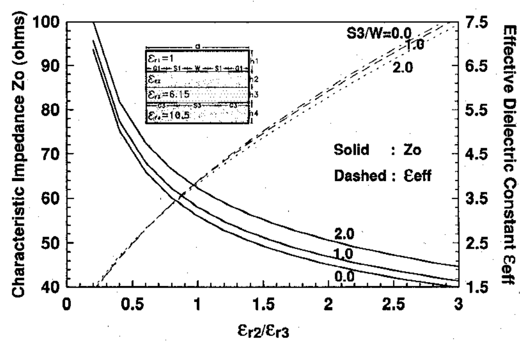

Fig. 4. Characteristic impedance and effective dielectric constant of a symmetric slot-coplanar line versus the central layers' relative dielectric constants. $a = 5h_1 = 20h_2 = 20h_3 = 5h_4 = 10\text{S}_1 = 10\text{W} = 100$ mils; $\varepsilon_{r1} = 1$; $\varepsilon_{r3} = 6.15$; $\varepsilon_{r4} = 10.5$.

on the strip; and $\tilde{G}$'s denote the spectral-domain Green's functions. The above equations can be solved for the unknown c's and d's. The total charge on the strip is then obtained, which is used to calculate the characteristic impedance and effective dielectric constant.

To obtain numerical results, we used the following basic functions to approximate the charge distributions on the strip and ground planes

$$\rho_{sj}(x) = \frac{\cos\left[(j-1)\pi\frac{x-S1-G1}{W}\right]}{\left[1-\left(\frac{2(x-S1-G1)-W}{W}\right)^2\right]^{1/2}}$$

$$\rho_{Gij}(x) = \begin{cases} \dfrac{\cos\left[(j-\frac{1}{2})\pi\frac{x-Gi}{Gi}\right]}{\left[1-\left(\frac{x}{Gi}\right)^2\right]^{1/2}}, & i = 1,3 \\ \dfrac{\cos\left[(j-\frac{1}{2})\pi\frac{x-a+Gi}{Gi}\right]}{\left[1-\left(\frac{a-x}{Gi}\right)^2\right]^{1/2}}, & i = 2,4 \end{cases}.$$

III. Numerical Results

Numerical results have been obtained for structures suitable for MIC's. Fig. 2 shows variations of the characteristic impedance and effective dielectric constant versus the lower-slot width for different widths of the upper slots. The strip and the lower slot are aligned at the center of the shield, and the widths of the upper slots are equal. As can be seen, the characteristic impedance and effective dielectric constant increase as the width of the lower slot increases. The change is significantly pronounced when the lower slot is small, while virtually unnoticed for a large slot. This phenomenon is predicted as the transmission line's capacitance per-unit-length reduces when the lower-slot width is increased, due to more fields penetrating into the bottom layer. Furthermore, the range of the lower-slot width that affects the behavior is smaller for smaller upper-slot width, as expected, due to a strong interaction between the strip and the coplanar ground planes when the upper slots are small.

Fig. 3 shows the effects of the height of the upper layer for different sizes of the lower slot. Both the characteristic impedance and effective dielectric constant increase and eventually approach constants as the height is increased. This behavior of the characteristic impedance is expected as the field between the strip and the upper shield is strong when the height is small, and reduces as it is increased. The increase of the effective dielectric constant is the consequence of an increased concentration of the field in the dielectric layers when the height increases. These changes are less for narrow, lower slots due to a strong confinement of the fields within the central substrate. However, when the lower slot is large, the energy concentrated near the upper slots increases, thereby escalating the influence of the upper shield.

Results of the characteristic impedance and effective dielectric constant as the relative dielectric constants of the central layers change are shown in Fig. 4. As the ratio of the dielectric constants of the central upper and lower layers is increased, the characteristic impedance and effective dielectric constant decrease and increase, respectively, due to an increase of the field strength in these layers. In addition, we observe maximum and minimum characteristic impedances when the dielectric constant of the upper layer is much smaller and larger, respectively, than that of the lower layer, corresponding to the weakest and strongest confinements of the fields within the central layers.

In Fig. 5, variations of the characteristic impedance and effective dielectric constant versus the location of the lower slot are studied. Interesting but expected results are observed here. When the slot is far away from the strip, the characteristic impedance and effective dielectric constant are constant, since the slot now has negligible influence on the transmission line's characteristics. However, as the slot approaches the strip, both the characteristic impedance and effective dielectric constant increase because more of the field lines penetrate the bottom layer, whose relative dielectric constant is higher than that of

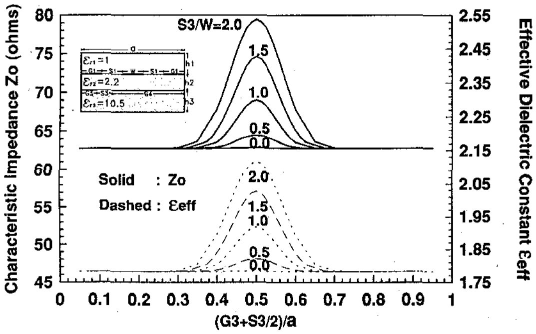

Fig. 5. Characteristic impedance and effective dielectric constant of an asymmetric slot-coplanar line versus the lower slot's location. $a = 5h_1 = 20h_2 = 5h_3 = 10\text{W} = 10\text{S}_1 = 100$ mils; $\varepsilon_{r1} = 1$; $\varepsilon_{r2} = 2.2$; $\varepsilon_{r3} = 10.5$.

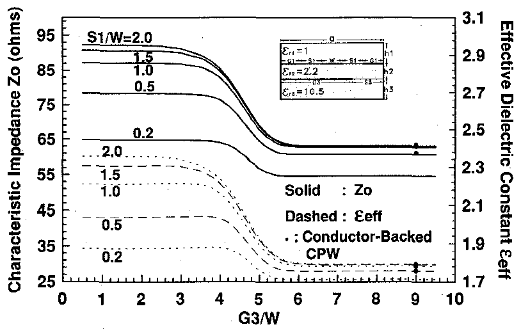

Fig. 6. Characteristic impedance and effective dielectric constant of a micro-coplanar line versus the lower ground. $a = 5h_1 = 20h_2 = 5h_3 = 10$ W = 100 mils; $\varepsilon_{r1} = 1$; $\varepsilon_{r2} = 2.2$; $\varepsilon_{r3} = 10.5$.

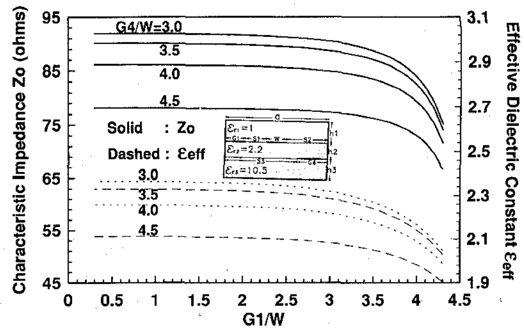

Fig. 7. Characteristic impedance and effective dielectric constant of a micro-coplanar line versus the coplanar ground's width. $a = 5h_1 = 20h_2 = 5$ $h_3 = 10\text{W} = 100$ mils; $\text{S}_2 = 45$ mils; $\varepsilon_{r1} = 1$; $\varepsilon_{r2} = 2.2$; $\varepsilon_{r3} = 10.5$.

the central layer. These changes are drastic for larger lower slots and also when the slot is close to the strip because of increased interactions between the lower shield, lower slot, strip, upper slots, and coplanar grounds. The maximum characteristic impedance and effective dielectric constant occur when the lower slot is centered underneath the strip, where maximum field lines enter the bottom substrate.

Effects of the lower ground on a micro-coplanar line having double coplanar grounds are illustrated in Fig. 6. The strip is aligned at the center of the shield, and the upper slots are identical. It is interesting to observe that, while the characteristic impedance and effective dielectric constant stay constant when the inner edge of the lower ground is far away from the strip, they decrease as the edge advances near the strip. As the lower ground increases in size, the transmission line changes from a two-substrate CPW ($\varepsilon_r = 2.2, 10.5$) to a single-substrate CPW ($\varepsilon_r = 2.2$), thus the characteristic impedance and the effective dielectric constant decrease because more of the field lines remain in the central dielectric layer as the ground plane gets larger. It should be noted here that the single-substrate CPW resembles a conductor-backed CPW, whose results calculated using the spectral domain technique [10] agree very well with those of a $G3/W = 9$ case, as seen in Fig. 6.

The characteristic impedance and effective dielectric constant of a micro-coplanar line having a single coplanar ground are plotted against the width of the coplanar ground in Fig. 7. The strip is aligned at the center of the shield. When the ground is far away from the strip, the characteristic impedance and effective dielectric constant are virtually unaffected. However, they decrease as the ground approaches the strip. The effective dielectric constant is reduced because more of the field lines exist in the top air layer as a result of increased interaction between the ground and the strip. The fringing field between the ground and the strip also increases as they get closer, producing a reduction in the characteristic impedance.

It should be noted, as observed from Figs. 2 and 5, that the characteristic impedance can be varied over a large range by simply changing the location and size of the lower slot. This unique tuning feature, in conjunction with the strip and upper slots, can be utilized to realize much larger impedance ranges than those of the conventional microstrip line and CPW. Our new slot-coplanar low-pass filter to be presented later exploits this feature in achieving a high selectivity. Similarly, Fig. 6 shows that we can tune the characteristic impedance over a large range by varying the lower-ground location. We also investigated the effect of changing the shield width, and found that an increase in the shield width only slightly affects the characteristic impedance and effective dielectric constant. This is due to the fact that the charge is distributed primarily along the edges of the strip and the inner edges of all the ground planes. The results and discussions presented are, therefore, applicable to the open transmission lines for MMIC applications.

IV. Slot-Coplanar Low-Pass Filter

In order to demonstrate possible applications of the proposed new planar transmission lines for MIC's and MMIC's and validate the developed analysis, we have designed and tested a seven-section low-pass filter with a cutoff frequency of 4 GHz using the slot-coplanar lines. The layout and design parameters of the filter are shown in Fig. 8. The employed slot-coplanar lines are described in Fig. 9's insert. The filter is basically a conventional high/low characteristic-impedance topology, whose selectivity depends significantly on the high/low impedance ratio. To achieve a high impedance ratio, the high- and low-impedance sections were formed both with a large slot and without a slot in the central substrate's underside. Fig. 9 shows the performance. Less than 0.5-dB insertion loss and more than 20-dB return loss were achieved. Good agreement between the calculated and measured results is also seen. The differences in the results are due primarily

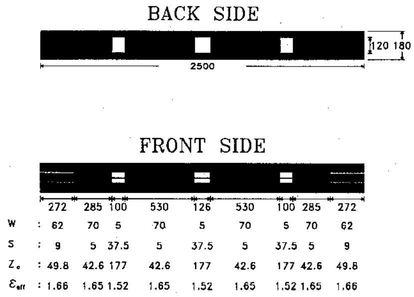

Fig. 8. The slot-coplanar low-pass filter. Dimensions are in mil.

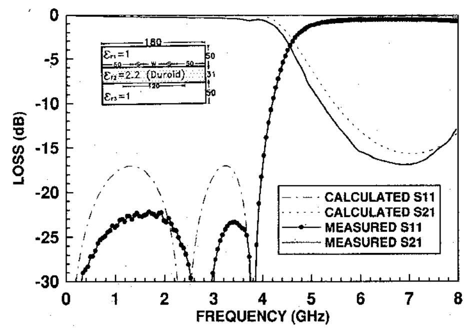

Fig. 9. Calculated and measured performances of the low-pass filter.

to the loss in the circuit which was not accounted for in the calculations.

V. Conclusion

Various new multilayer planar transmission lines have been proposed for possible use in MIC's and MMIC's. Their study, based on the spectral domain method, has been presented. The new transmission lines have a wide impedance range and are flexible and able to realize miniaturized, densely packed integrated circuits. They also have all the inherent characteristics of the microstrip line and CPW. Furthermore, we expect that they have significantly less interline coupling, cross talk, and distortion through suitable substrate selections. We are investigating these problems using a full-wave method, and results will be reported in the future. The proposed transmission lines should therefore be good candidates for implementation in MIC's and MMIC's to improve size, cost and performance. As an example to demonstrate possible applications in MIC's and MMIC's, a low-pass filter employing the new slot-coplanar lines was developed with less than 0.5-dB insertion loss and more than 20-dB return loss. Good agreement between the filter experimental results and those predicted theoretically has been observed, which validates the developed analysis for the transmission lines.

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