New Miniature Broad-Band CPW-to-Slotline Transitions

Khelifa Hettak, Nihad Dib, *Senior Member, IEEE*, A. Sheta, Amjad A. Omar, Gilles-Y. Delisle, *Fellow, IEEE*, Malcolm Stubbs, and Serge Toutain

***Abstract*—This paper proposes a novel class of uniplanar coplanar waveguide (CPW)-to-slotline transitions, which is particularly suitable for monolithic millimeter-wave integrated circuits. Instead of using CPW series stub printed in the ground plane, as the case in classical CPW-to-slotline transition, this paper shows the capability to use a CPW series stub printed in the center conductor of the CPW. Compared to classical CPW-to-slotline transitions, the proposed transitions have the following advantages: additional degrees of freedom, lower radiation loss, larger bandwidth, higher compactness, and a major reduction of the number of air bridges that are potentially expensive to build. One alternative configuration that appears to have some merit involves the use of the slotline ring resonator, which does not suffer from open-end or short-end effects and, therefore, gives more accurate resonance frequency, provides an accurate localized zero or infinite impedance point, and maintains low- or high-input impedance values over a wide frequency range, depending on the feed type. A principle of achieving such high-quality transitions is detailed and also confirmed by experimental and theoretical results, which are in good agreement up to 50 GHz. A maximum fractional bandwidth of 160% is achieved for a 10-dB return loss, and the corresponding insertion loss is less than or equal to 2 dB.**

I. INTRODUCTION

AN INCREASING system complexity leads to new challenges in circuit design. One way to cope with this is the combination of different types of transmission lines to achieve optimal performance. Indeed, the association of different planar structures of propagation brings interesting, simple, and original circuits. This is notably true in uniplanar technology where the implementation of some functions necessitates the coexistence of two structures of propagation: the coplanar waveguide (CPW) and the slotline. An example of this is the CPW-to-slotline transition, which is a fundamental passive component in microwave and millimeter-wave integrated circuits [(M)MIC's]. The properties of this transition have been a topic of considerable interest, where it is imperative to dispose a good transition so as not to degrade the performance of some devices such as antenna structures, balanced mixers, and other microwave circuits [1]–[6]. The research for new CPW-to-slotline configurations with wider bandwidth has been the subject of many papers in the literature and much effort continues to be expended [7]–[13]. The challenge is to achieve compact transition architectures with lower loss, less radiation and broader bandwidth, which can be easily incorporated in microwave integrated circuit/monolithic microwave integrated circuit (MIC/MMIC), and antenna applications operating in the millimeter-wave band. This is the spirit in which this paper is embedded. It focuses on the design of new topologies of CPW-to-slotline transitions with the purpose of obtaining optimum matching between the CPW and slotline and to reduce radiation loss.

Theoretically, all stubs and transmission lines must have the same characteristic impedance to maintain a good match over a broad frequency range [9]. However, this condition is not valid due to the unequal dispersion between slotline and

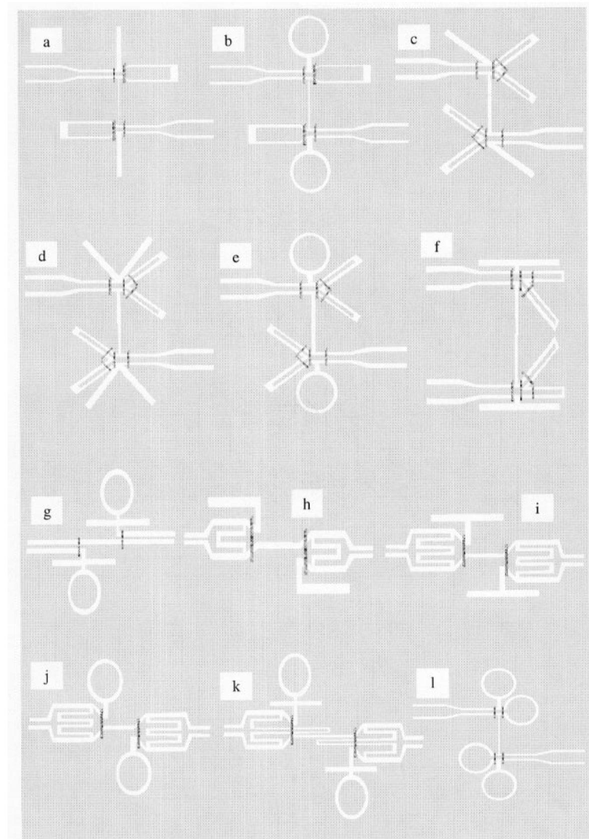

Fig. 1. New class of wide-band CPW-to-slotline transitions.

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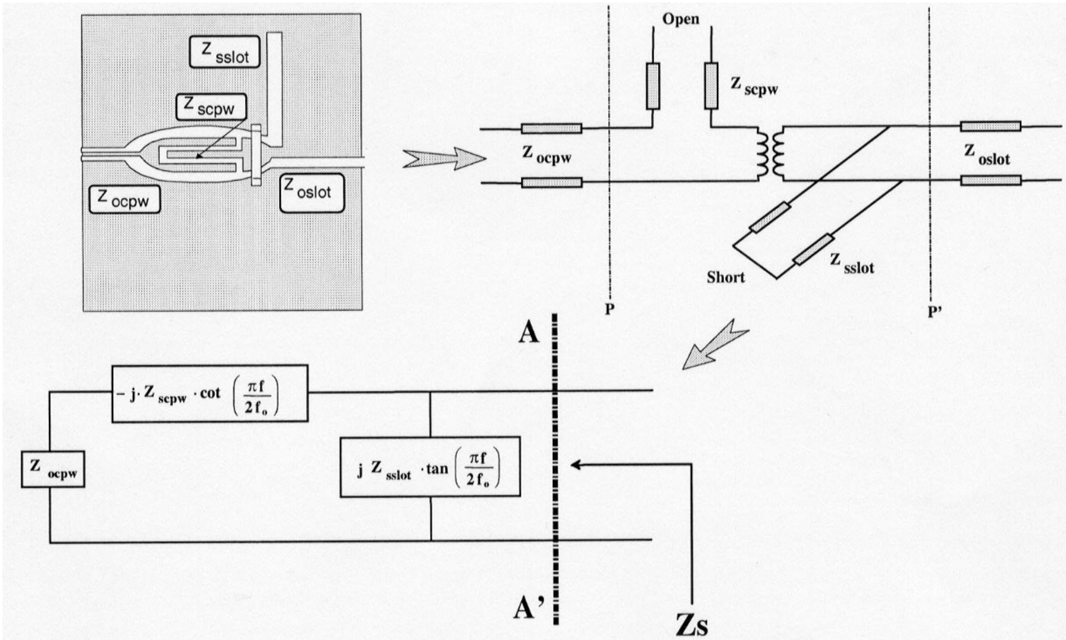


Fig. 2. New CPW-to-slotline transition and its equivalent circuit.

CPW. For this purpose, it is necessary to analyze the physical evolution of the different parameters of the CPW-to-slotline transition in order to develop geometric configurations with larger bandwidths. Considering that the bandwidth performance of the transition depends strongly on the values of the characteristic impedances of the used stubs, the difficulty in realizing low-impedance levels in CPW and high-impedance levels in slotline constitutes a serious limitation in the design, particularly at high frequencies. While the upper limit of realizable characteristic impedance is set by manufacturing tolerances, the lower limit depends on the onset of higher order modes that occurs when the transverse dimensions become comparable to the wavelength or to longitudinal dimension. A typical lower limit is 20–25 Ω for CPW and a higher limit is 90–100 Ω for slotline.

In this paper, improved CPW-to-slotline transition topologies are proposed and studied both experimentally and theoretically (see Fig. 1). These new forms of CPW-to-slotline transitions indicate, first, the wide range of flexibility and scope for innovation that uniplanar technology offers and, secondly, provides an alternative yet compact structures compared to classical configuration [Fig. 1(a)]. Section II starts with the establishment of optimal design criteria, which are required to design wide-band CPW-to-slotline transitions. A comparison between the classical [Fig. 1(a)] and the new miniature CPW-to-slotline transition [Fig. 1(h)] is also presented in Section II. In Section III, several new designs are developed to extend the bandwidth, as illustrated in Fig. 1. In Section IV, a novel CPW-to-slotline transition using slotline ring alone is presented.

II. Optimal Design of CPW-to-Slotline Transition

The classical back-to-back CPW-to-slotline transition is presented in Fig. 1(a). This transition consists of a slotline and a CPW that intersect at the right angle. For compensation, CPW, and slotline stubs, each of length $\lambda_g/4$ at the design frequency are connected in series and in parallel, respectively. Two air bridges are also used to connect the CPW ground planes. Fig. 2 shows a new CPW-to-slotline transition and its equivalent circuit where f_0 is the design frequency. It should be noted that the same equivalent circuit holds for the classical transition. The first step in this study aims to establish the optimal design criteria that are determined from the analysis of the equivalent circuit of the transition. As shown in Fig. 2, the impedance looking in the plane AA' can be expressed as

$$Z_s = Z_{ocpw} \frac{1 - j\left(\frac{Z_{scpw}}{Z_{ocpw}}\right)\cot\phi}{1 - j\left(\frac{Z_{scpw}}{Z_{sslot}}\right)\cot^2(\phi) - j\left(\frac{Z_{ocpw}}{Z_{sslot}}\right)\cot\phi}$$

with

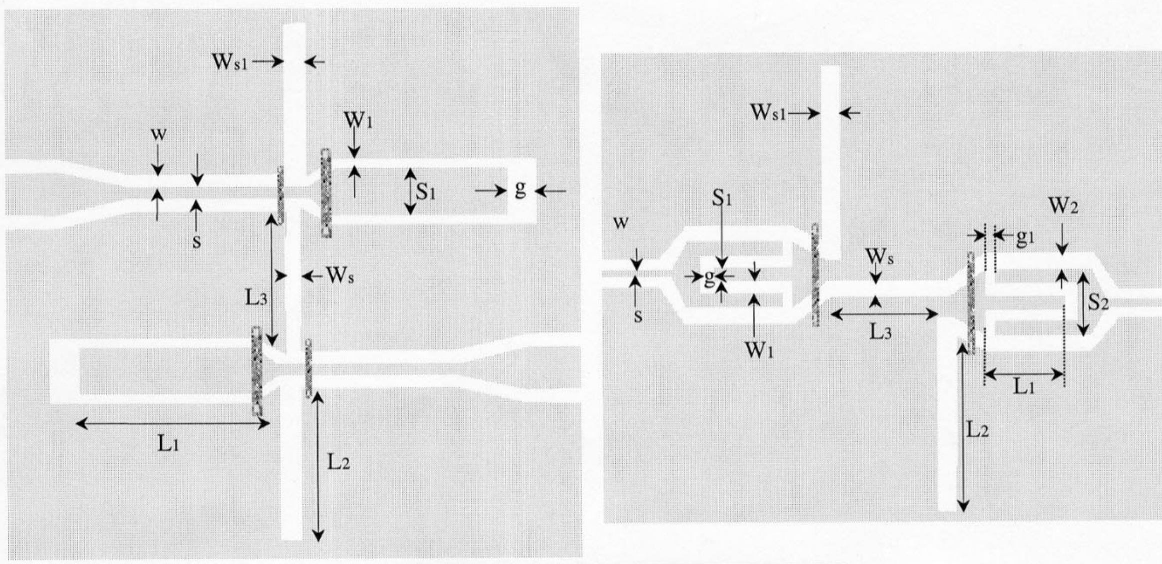
$$\frac{\phi = \pi f}{2f_o.} \tag{1}$$

It is clear that the largest bandwidth is obtained when $Z_s = Z_{ocpw}$, which leads to (2) as follows:

$$1 - j\left(\frac{Z_{scpw}}{Z_{ocpw}}\right)\cot\phi = 1 - j\left(\frac{Z_{scpw}}{Z_{sslot}}\right)\cot^2(\phi) - j\left(\frac{Z_{ocpw}}{Z_{sslot}}\right)\cot\phi. \tag{2}$$

This equation holds if

$$Z_{scpw} = \frac{Z_{ocpw}^2}{Z_{sslot}} \quad \text{and} \quad \frac{Z_{scpw}}{Z_{sslot}} \to 0. \tag{3}$$



Parameters	Value	Units
s	30	μm
w	25	μm
s1	130	μm
w1	25	μm
ws1	110	μm
ws	25	μm
g	100	μm
Zocpw	60	Ω
Zoslot	60	Ω
Zscpw	40	Ω
Zsslot	90	Ω
L1	2.1	mm
L2	2.4	mm
L3	2.5	mm
w2	150	μm
s2	230	μm
g1	50	μm

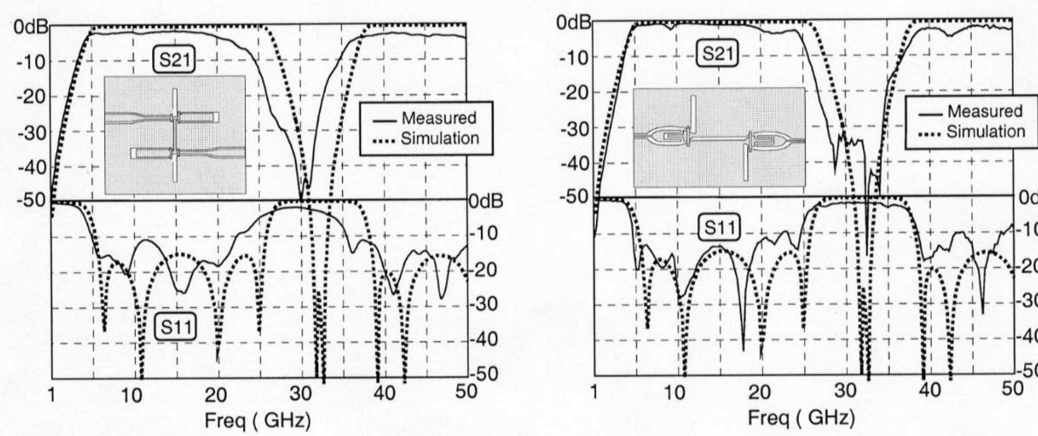


Fig. 3. Experimental and simulated results for classical and compact back-to-back transitions.

Replacing Z_{scpw} by Z^2_{ocpw}/Z_{sslot}, the impedance Z_s becomes

$$Z_s = Z_{ocpw} \frac{1 - j\left(\dfrac{Z_{ocpw}}{Z_{sslot}}\right)\cot\phi}{1 - j\left(\dfrac{Z_{ocpw}}{Z_{sslot}}\right)^2 \cot^2(\phi) - j\left(\dfrac{Z_{ocpw}}{Z_{sslot}}\right)\cot\phi}. \tag{4}$$

From this equation, it is evident that the best results are obtained when Z_{sslot} has a very high value. In this case, the ratio Z_{ocpw}/Z_{sslot} tends to zero, which cancels the reactive part and leads to a very large bandwidth since $Z_s = Z_{ocpw}$. A first idea is to choose the highest value for $Z_{sslot}$and the lowest value for Z_{scpw} allowed by the technological process. The difficulty in realizing low-impedance levels in CPW and high-impedance

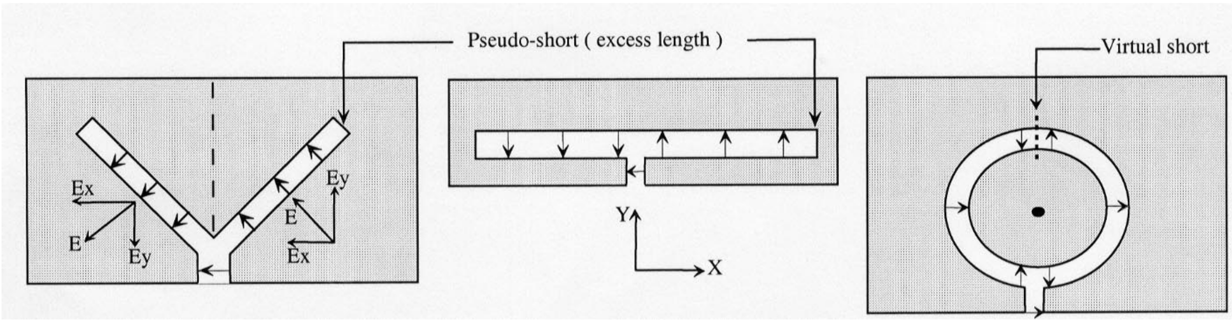


Fig. 4. Electric-field distribution of three types of slotline resonators V-slot rectangular slot. (a) V-slot. (b) Rectangular slot. (c) Slot ring.

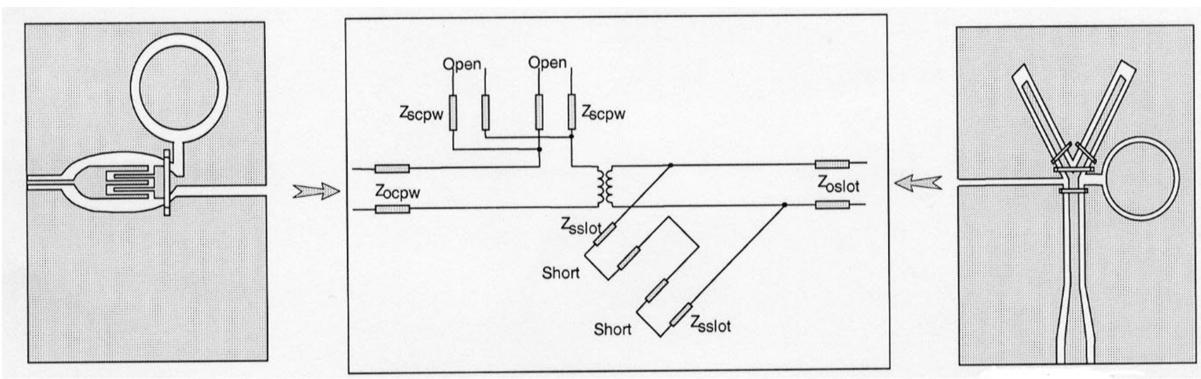
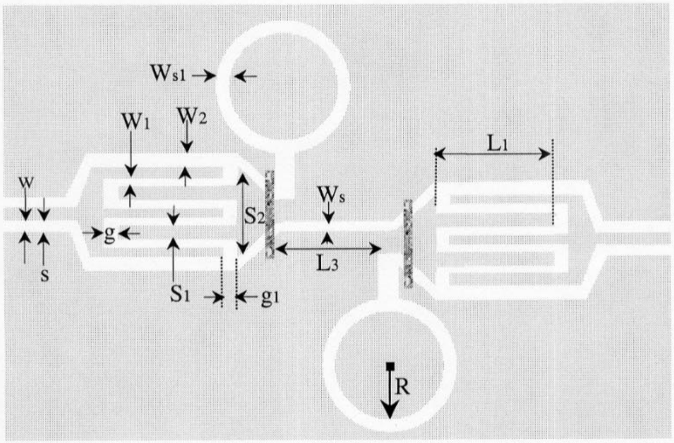


Fig. 5. Multistubs configurations of the CPW-to-slotline transition and their equivalent circuit that uses $\lambda_g/2$ circumference slotline ring resonator and uniform double $\lambda_g/4$ CPW series stubs: (a) printed on the center conductor and (b) ground plane.

levels in slotline constitutes a serious limitation in the design of a broad-band CPW-to-slotline transition, particularly at high frequencies. While the upper limit of realizable characteristic impedance is set by manufacturing tolerances, the lower limit depends on the onset of higher order modes. In the practical case, characteristic impedance of about 40 Ω is used for the CPW open stub, on account of the technological limitations (smallest slot and strip widths), and 90 Ω for slotline because of electrical restrictions (radiation effects). The choice of these characteristic impedances is mainly dictated by technological constraints (limitation of slot and ribbon widths in photoetching is 25 μm) and by the concern to minimize the effect of discontinuities, and notably the parasitic radiation. Indeed, it is possible to obtain very low (20 Ω) impedance CPW and high (100 Ω) impedance slotline. That, however, implies large transverse dimensions, resulting in an increased sensitivity of the impedance to dimensional variations. This is very critical, and means that uncertainties in the process of manufacturing can influence severely the electrical behavior. Moreover, large slot widths always result in parasitic radiation that affects the transition performance.

To date, CPW series stubs printed on the ground plane have been used as the stub of compensation in the majority of CPW-to-slotline transitions developed thus far [see Fig. 1(a)–(f)]. This requires large area, causes high radiation loss, and necessitates the use of air bridges to suppress the parasitic coupled slotline mode. One method to circumvent this problem is to employ the CPW series stub printed on the center conductor (Fig. 2), which provides low loss, longitudinal symmetry, and compactness [16]. This also eliminates the need for two air bridges, and thus, simplifies the fabrication process. For the sake of comparison, Fig. 3 illustrates two back-to-back transitions, one realized with CPW series stub printed on the ground plane and the other on the center conductor. The two transitions were fabricated with a center frequency $f_o = 15$ GHz using alumina substrates ($\varepsilon_r = 9.9$, $h = 0.254$ mm) and accurate on-wafer measurement were performed over the frequency range of 1–50 GHz. As shown in Fig. 3, compared to the classical structure, the new transition gives broader bandwidth, lower radiation loss, smaller size and reduction of the number of air bridges. Along with experimental results, Fig. 3 shows simulated S-parameters obtained using HP-MDS. In this simulation, the end inductance and capacitance associated with the short-end slotline stub and open-end CPW stub, respectively, are introduced in the equivalent circuit. These end effects are evaluated using the full-wave space-domain integral-equation technique [15]. Parasitic effects due to junctions and air bridges are neglected. It can be noticed that there is a very good agreement between the theoretical and experimental results for the compact configuration. The fractional bandwidth for the new transition is around 130% for a 10-dB return loss compared to 115% for the classical one.



Parameters	Value	Units
s	30	μm
w	25	μm
s_1	130	μm
w_1	25	μm
w_{s1}	110	μm
w_s	25	μm
g	100	μm
Zocpw	60	Ω
Zoslot	60	Ω
Zscpw	40	Ω
Zsslot	90	Ω
L_1	2.1	mm
R	0.76	mm
L_3	2.5	mm
w_2	230	μm
s_2	435	μm
g_1	50	μm

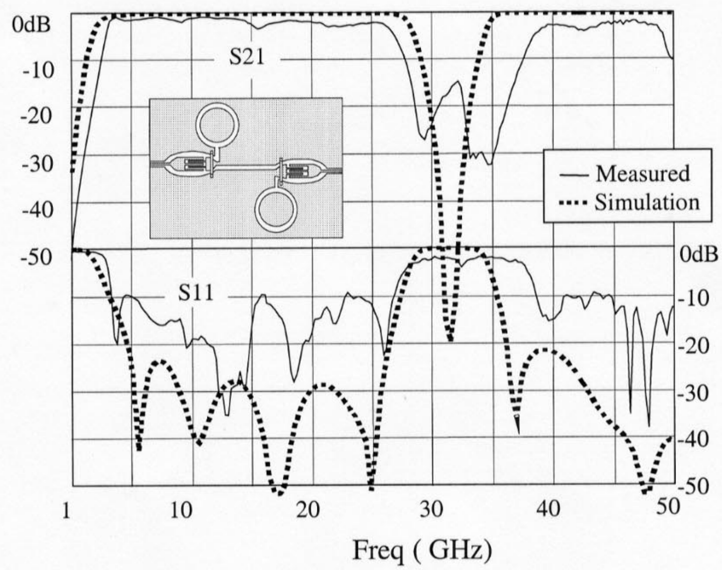


Fig. 6. Frequency response of the new back-to-back CPW-to-slotline transition.

III. Alternative Solutions to Obtain Better Matching

With the purpose of overcoming the above difficulty, a new method to design low- and high-impedance levels associated with CPW and slotline stubs, respectively, is introduced in this section. A low-impedance coplanar series stub and high-impedance slotline parallel stub can be realized by the connection of several single stubs in parallel and series, respectively. With such structures, it is possible to obtain very low impedances (typically less than 20 Ω) or high impedances (typically larger than 200 Ω) in uniplanar technology. This is hardly achievable in microstrip technology. In others words, using parallel connection of many single CPW stubs can drastically reduce the total input impedance value. Similarly, using series connection of many single-slotline stubs increases the total input impedance value. One possibility is to choose a double $\lambda_g/4$ CPW stubs configuration with a low $Z_{s\text{cpw}}$ value and a double $\lambda_g/4$ slotline stubs configuration with a high $Z_{s\text{slot}}$ value, as shown in Fig. 1(d). This, in effect, reduces the contribution of the terms that depend on frequency in (4).

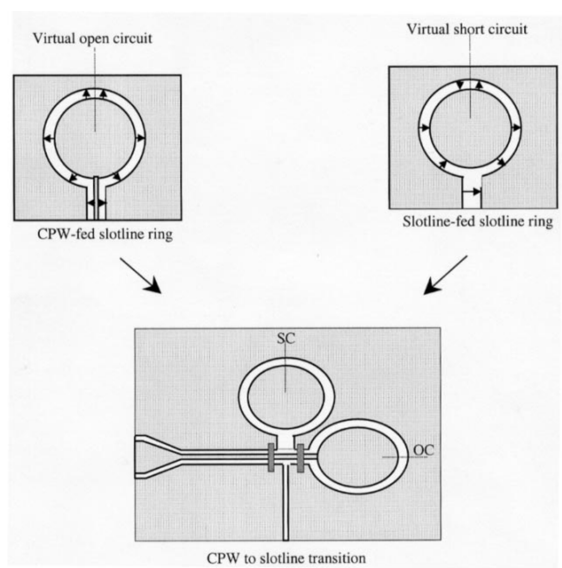
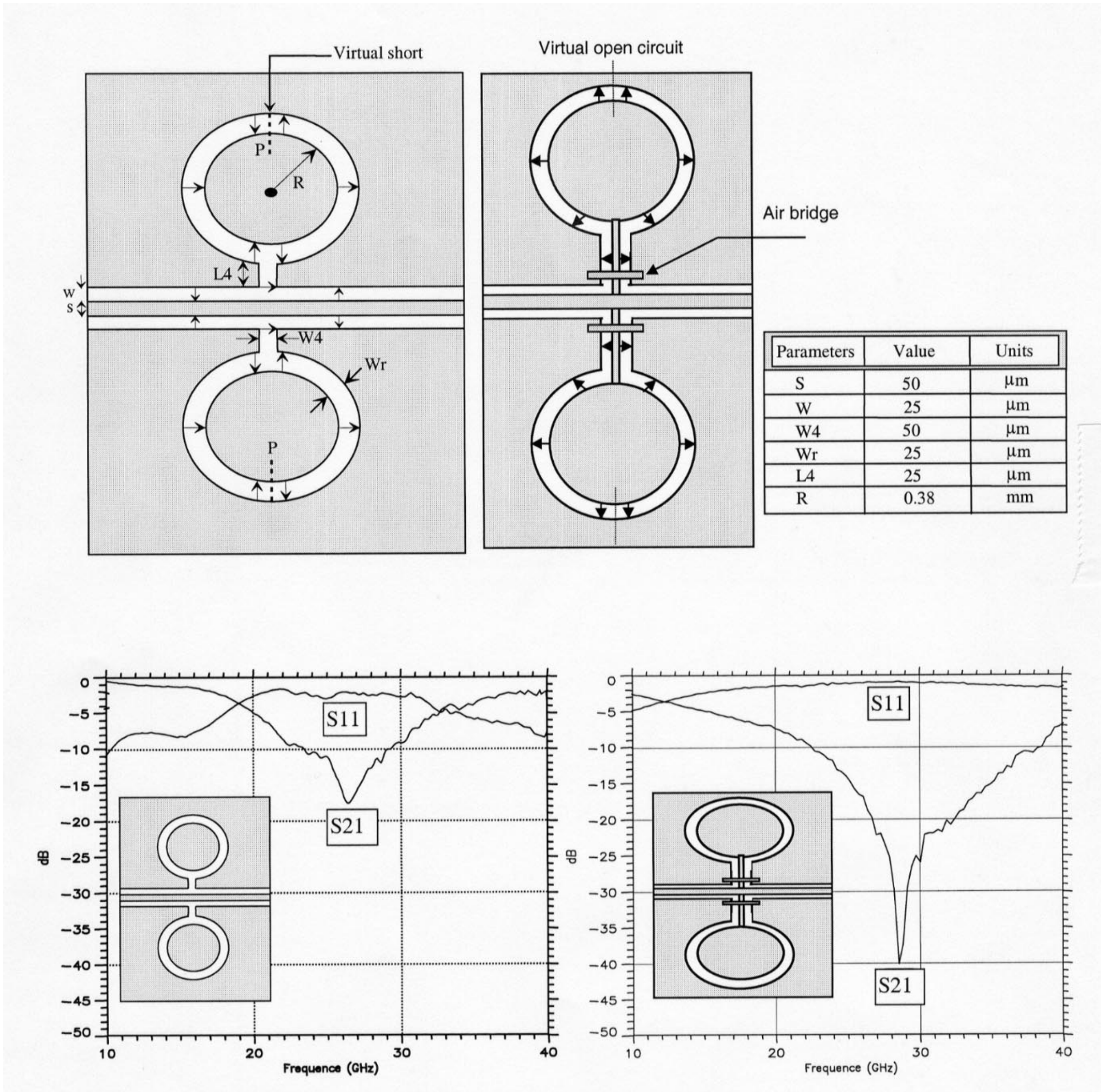


Fig. 7. Novel CPW-to-slotline transition configuration that uses slotline ring only.



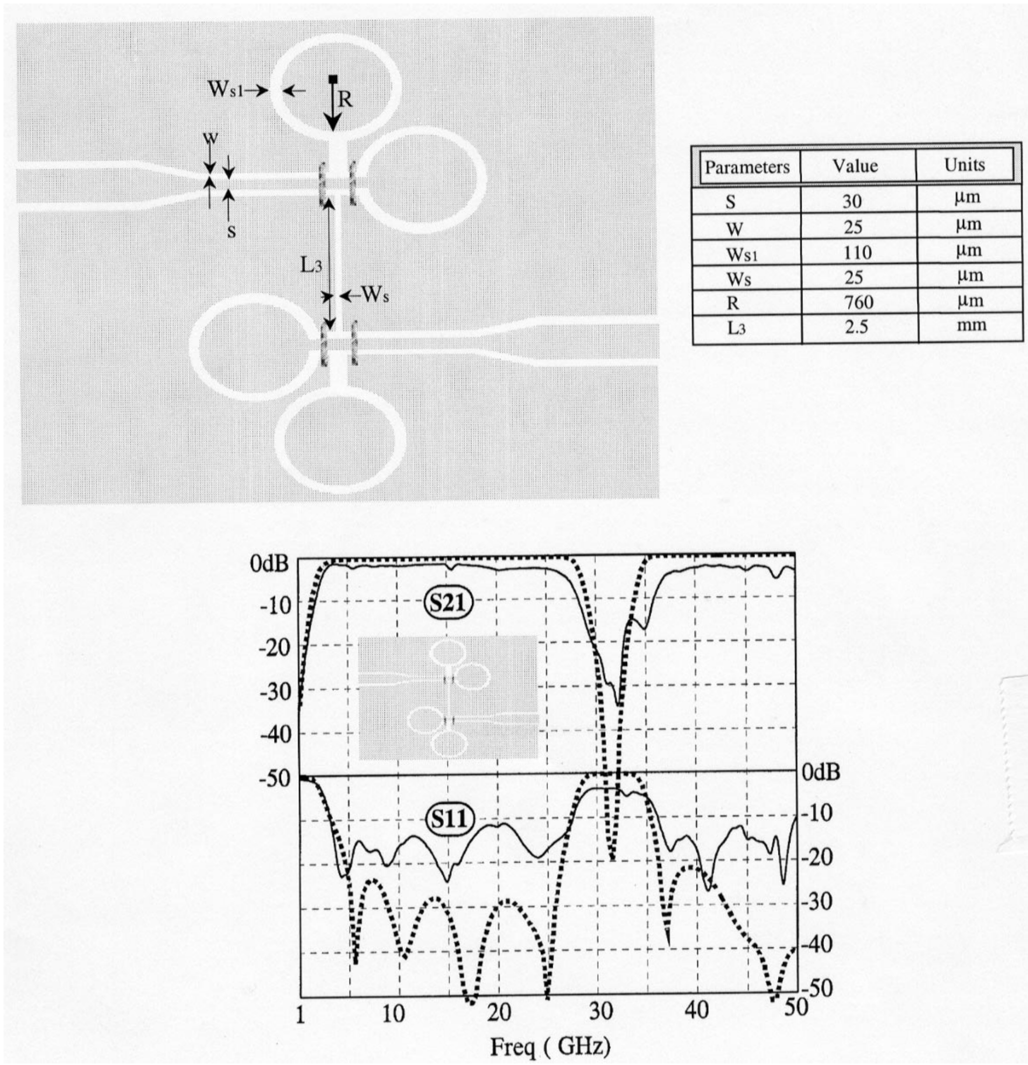
Parameters	Value	Units
S	50	µm
W	25	µm
W4	50	µm
Wr	25	µm
L4	25	µm
R	0.38	mm

Fig. 8. Experimental results for the double slot ring resonators ($h = 0.254$ mm, $\varepsilon_r = 9.9$).

However, it is also advisable to study the optimal geometric configuration of the slotline and CPW stubs.

Concerning the implementation of the double $\lambda_g/4$ slotline stubs, the three configurations shown in Fig. 4 seem appropriate. While the first configuration [Fig. 4(a)] is very easy to implement, it partially radiates and needs some end correction. To avoid radiation, the second configuration [Fig. 4(b)] seems the most appropriate. Experimental results showed that the first resonance of this rectangular slot resonator occurs when the length of the slot is approximately equal to $\lambda_g/2$. The two half-parts of the resonator are excited with a 180° phase difference via a small slotline feed and, thus, radiation problems are avoided. The major advantage of the slot ring resonator, shown in Fig. 4(c), is the existence of a virtual short in comparison with the rectangular slot resonator where the pseudo-short ends are equivalent to excess lengths that become significant at high frequencies [15].

With regard to the implementation of the double $\lambda_g/4$ CPW stubs, the two configurations shown in Fig. 5 seem appropriate. The topology illustrated in Fig. 5(a) represents one possible way to build these two stubs in the center conductor of the CPW line instead of the ground plane. This new structure combines the advantages of the use of the center conductor with the advantages of slotline ring resonator, and reduces the number of air bridges from four down to one. An experimental circuit (Fig. 6) was designed at$f_o = 15$ GHz and fabricated on alumina substrate ($\varepsilon_r = 9.9h = 0.254$, $h = 0.254$mm). Experimental results and simulation results obtained using HP-MDS are shown in Fig. 6, which are in good agreement. It should be noted that in the HP-MDS simulations, the discontinuity effects are not taken into account, except the open-circuit capacitance for the CPW stubs. This explains the discrepancy between the simulated and measured return loss in the passband. As expected, the new transition exhibits a larger bandwidth than those shown



Parameters	Value	Units
S	30	µm
W	25	µm
Ws1	110	µm
Ws	25	µm
R	760	µm
L3	2.5	mm

Fig. 9. Frequency response of the new back-to-back transition built from slot ring resonators only.

in Fig. 3. The fractional bandwidth is around 160% for a 10-dB return loss. The corresponding insertion loss is less than or equal to 2 dB. It should be noted that the transmission-loss variation with frequency is mainly due to the feeding CPW's and slotline length between the two transitions.

Pushing this reasoning further and exploiting the flexibility of the uniplanar technology, many other transition configurations are feasible, as shown in Fig. 1. In light of this, one alternative configuration that appears to have some merit would involve solely integrating the slotline ring resonator [see Fig. 1(l)], which is the subject of Section IV.

IV. A New Broad Band CPW-to-Slotline Transition Using Slotline Ring Only

The slotline ring resonator is a fundamental passive component in (M)MIC monolithic circuits and its integration in transitions' design is a topic of considerable interest [14]. The possible uniplanar configurations of a slotline ring resonator can be classified in the following two types: CPW-fed ring and slotline-fed ring. Fig. 7 shows the physical configurations and schematic diagram of E-field distribution for the two types. It also presents a new compact CPW-to-slotline transition that uses slotline ring only. Compared to the slotline linear resonator, the slotline ring resonator does not suffer from open-end or short-end effects and, therefore, gives more accurate resonance frequency. It also provides an accurate localized zero or infinite impedance point, and maintains low- or high-input impedance value over a wide–frequency range depending on the feed type. In order to understand the electromagnetic behavior of these resonators and their impact on the transition performance, it is necessary to study their frequency response. Fig. 8 shows a comparison between the double slot ring resonator fed by slotline and the one fed by CPW with the same dimensions. It can be noticed that both configurations have approximately the same resonant frequency, which indicates the ability of the slotline ring resonator to substitute simultaneously both CPW and slotline stubs.

From these considerations, a novel variant of broad-band CPW-to- slotline back-to-back transition was designed at $f_0 = 15$ GHz and fabricated on alumina substrate ($\varepsilon_r = 9.9$, $h = 0.254$ mm). Fig. 9 shows the physical configuration and

S-parameters of this transition. The overall agreement between the measured and modeled insertion-loss and return-loss of two back-to-back transitions is good. The discrepancies are due to the fact that the discontinuities effects are not taken into consideration when modeling the transition using HP-MDS. A maximum fractional bandwidth of 160% is achieved for a 10-dB return loss, and the corresponding insertion loss is less than or equal to 2 dB. The experimental results presented in Fig. 9 provide very strong indication as to the exciting broad bandwidth and lower radiation compared to the conventional transitions. It should be noted that the experimental results in Fig. 9 are less frequency sensitive than those in Fig. 6.

V. Conclusions

(M)MIC integrated circuits using uniplanar technology yield innovative and high-performance components and subsystems. This paper focused on several new designs of CPW-to-slotline transitions, which have been proven to work well in the millimeter-wave region. A principle of achieving these high-quality transitions was detailed and also confirmed by experimental and simulation results over a large frequency range (1–50 GHz). A maximum fractional bandwidth near 160% was achieved for a 10-dB return loss. Compared to the conventional CPW-to-slotline transition, the advantages that may be derived from the use of the proposed framework are: 1) more degrees of freedom; 2) less radiation loss; 3) wide-band performance, which can be improved by the appropriate choice of special element topologies such as slot ring and CPW series stub patterned in the center conductor; 4) high compactness; and 5) reduction of the number of air bridges, which are potentially expensive to build. The new transitions have the potential to be used as building blocks for the emerging wireless communications industry, in general, and in the design of low-cost uniplanar (M)MIC's such as couplers, mixers, and antennas, in particular [13].

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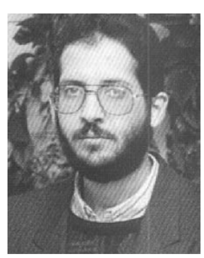
Dr. Hettak was a recipient of the France Telecom Scholarship.



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