Co-Layered Integration and Interconnect of Planar Circuits and Nonradiative Dielectric (NRD) Waveguide

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***Abstract*—A concept of hybrid integration between planar circuits and a nonradiative dielectric (NRD) waveguide is proposed in this paper with preliminary experiments. This approach utilizes co-layered arrangement of the two dissimilar structures, which allows the NRD-guide in direct contact with (or surface mounted on) the planar circuits. Two basic building-block schemes are presented that involve microstrip line and coplanar waveguide (CPW) with the NRD-guide. The first is to deposit the NRD-guide on the top of a relatively thin microstrip substrate, thus forming unbalanced NRD-guiding hybrid circuits, while the second is to design CPW circuits directly etched on the ground planes of the NRD-guide. The unbalanced NRD-guide is subject to a certain leakage loss, but at a negligible level, and it may even be suppressed completely in certain circumstances. Such an integration technique is found consistent with the concept of low-loss interconnects at millimeter-wave frequencies. In other words, the NRD-guide can be used for viable interconnects of co-layered planar circuits with a simple "put and cover" procedure. Measured results of several co-layered hybrid transitions/baluns indicate that satisfactory transmission properties can readily be achieved. The new building blocks are expected to provide an alternative design approach to three-dimensional multilayered millimeter-wave circuits and systems.**

***Index Terms*—Hybrid-integration technology, interconnects, millimeter-wave circuits, nonradiative-dielectric guide, 3-D multilayered IC's, transition/balun.**

I. Introduction

MILLIMETER-WAVE planar circuits are designed with planar transmission lines such as microstrip, coplanar waveguide (CPW), suspended stripline, and so on. The most important issue in dealing with the millimeter-wave design is to use high-yield and high-performance circuit building blocks at low cost. Newly emerging approaches show promising features for high-density circuit designs, namely, three-dimensional (3-D) monolithic microwave integrated circuits (MMIC's) and low-temperature cofired ceramic (LTCC) technology [1]. Nevertheless, challenging problems are often encountered in the design of low-loss passive integrated circuits (IC's), e.g., high-Q bandpass filter, to which the planar geometry is fundamentally not amenable. Often, the classic waveguide technique is necessary in the design of passive circuits to overcome the inherent difficulties of planar structure. In this connection, the 3-D hybrid design of planar and nonplanar structures becomes popular.

The nonradiative dielectric (NRD)-guide has been known as a very promising design platform for millimeter-wave IC's owing to its nonradiating and low-loss transmission properties [2]–[4]. However, an effective integration with active device is difficult in the original version of the NRD-guide technology in view of potential ductile and/or brittle problems, as well as required precision mechanical assembling and/or alignment of multiple dielectric strips. To solve these problems, a hybrid integration technology of planar circuit and NRD-guide was proposed and developed, which offers a unique possibility of exploiting inherent complementary advantages of each individual building block while eliminating (at least partly, if not completely) potential drawbacks [5].

In this paper, a concept is presented for the circuit design of planar/NRD structures, which features co-layered hybrid integration of the two dissimilar structures without resorting to intermediate aperture couplings, as reported in [5]. Preliminary experiments are made to validate the new schemes. Our proof of concept has been completed with a successful demonstration of two classes of microstrip-to-NRD-guide and CPW-to-NRD-guide transitions/baluns. Measured results show that satisfactory transmission properties can readily be obtained. This concept is rather useful if monolithic circuits are required to integrate with the NRD-guide. In addition, this concept points to a possibility of designing unique low-loss interconnects of adjacent interface-to-interface or layer-to-layer planar circuits via an NRD-guide. In the following, the proposed 3-D integration and interconnect schemes are presented and discussed with respect to transmission efficiency between these structures.

II. Co-Layered Integration and Interconnect Schemes

A. Co-Layered Integration of Unbalanced NRD-Guide with Microstrip Circuits

1) Unbalanced NRD-Guide: Without involving planar lines and circuits, Fig. 1 depicts the geometry of an unbalanced NRD-guide, which consists of a core dielectric strip deposited on the top of a relatively thin dielectric substrate. The whole structure is sandwiched between two parallel metallic plates in the same way as required in the conventional NRD-guide. The core dielectric block can thus be used to design an NRD-guide with a similar rule as used for the conventional NRD-guide, but in the presence of the dielectric substrate. Therefore, the exact

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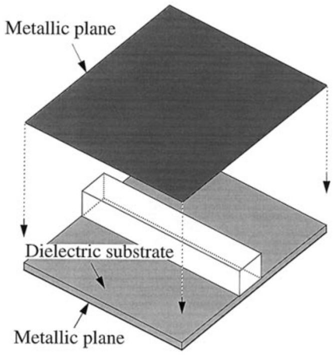

Fig. 1. 3-D geometrical view of proposed unbalanced NRD-guide integrated with a relatively thin dielectric substrate.

NRD-guide modes are difficult to formulate in an analytical manner. A quasi-LSM_{01} fundamental mode should be considered along the new NRD-guide because of the layered dielectric substrate. Characteristics of the unbalanced NRD-guide are expected similar to the original NRD-guide since the electrically thin dielectric layer may solely modify little field profiles and guided wave features. Hence, the proposed structure should be able to preserve a great deal of the desired properties of the conventional NRD-guide.

Of course, a possible leakage may be generated from the proposed structure since the vertical symmetry of structure cannot be guaranteed. However, this unwanted scenario may be corrected with two possible remedies. First, some specific geometrical asymmetry may not always generate a leakage loss within certain frequency ranges because of modal cancellation effects, as reported in [6]. Second, bilateral packaging/shielding structure could be used to eliminate circuit-to-circuit couplings due to the leakage even though there is an issue of effectiveness. Generally, such a leakage loss may be very small or even negligible within certain frequency ranges if adequate dimensions of the structure are chosen, which require, in any case, careful field-theory-based modeling and design.

2) Design of Microstrip-to-Unbalanced NRD-Guide Transition/Balun: Fig. 2 shows the new integration scheme of an unbalanced NRD-guide with microstrip circuits. This is made possible by a geometrical arrangement in that the microstrip circuits are formed on a relatively thin dielectric substrate and the circuit integration is achieved by a line-to-guide coupling, as described in Fig. 2(a). In this case, the planar line is oriented perpendicularly with respect to the NRD-guide, similar to the transition of a strip line to an NRD-guide, as reported in [7], such that the two dissimilar structures are designed with a great freedom, except for the coupling section. Excellent coupling characteristics are expected from this transition/balun, which will be discussed in a subsequent section. Underlying advantages of the proposed technique can be simply postulated by the fact that the planar circuits are useful for the design of active circuits, while the NRD-guide can be exploited for high-Q low-loss passive and other types of components. Fig. 2(b) shows a back-to-back interconnect of two distant microstrip lines on the same substrate for the purpose of experiments. Obviously, the removal of the upper metallic plate cover and NRD-guide will disconnect the two lines. This observation suggests that the NRD-guide can effectively serve as a low-loss interconnect for the two separate microstrip lines.

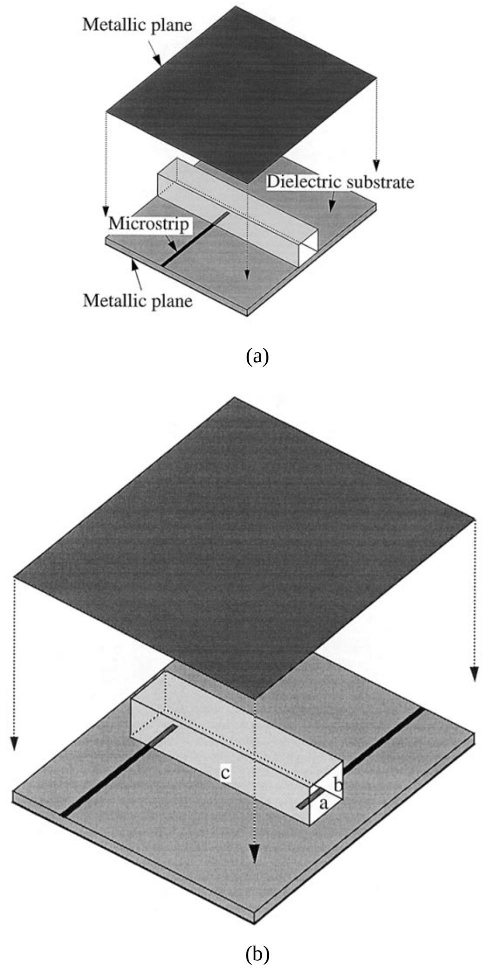

Fig. 2. Co-layered integration and interconnect scheme of the unbalanced NRD-guide with a microstrip planar circuit. (a) Transparent view of the 3-D geometry for the integration of the two dissimilar structures. (b) Experimental back-to-back arrangement of two microstrip line-to-unbalanced NRD-guide transitions/baluns.

Successful integration and interconnect of the microstrip lines with the unbalanced NRD-guide rely on the design of a good transition/balun that links the two dissimilar structures. Such a design procedure is crucially important that requires a low signal-path loss and a miniaturized coupling section. In our transition/balun design, as highlighted in Fig. 3(a), the width of microstrip line is W, the penetration depth of the open-ended microstrip line into the core dielectric block is L_s, and the NRD open-end distance with respect to the center of the microstrip line is L_w. The adequate choice of L_s and L_w is critical in exciting the quasi-LSM_{01} mode in this unbalanced NRD-guide and also in obtaining a good impedance matching. As described in Fig. 3(b), electrical performance of the transition/balun may be improved by appropriately reshaping the microstrip line open-end, which needs further detailed investigations. In our case studies, the microstrip line and unbalanced NRD-guide are made of a 20-mil Duroid substrate ($\varepsilon_r = 2.33$) and Polystyrene block ($\varepsilon_r = 2.56$), respectively.

This new scheme is different from our previously studied hybrid integration of planar circuits/NRD-guide, in which a

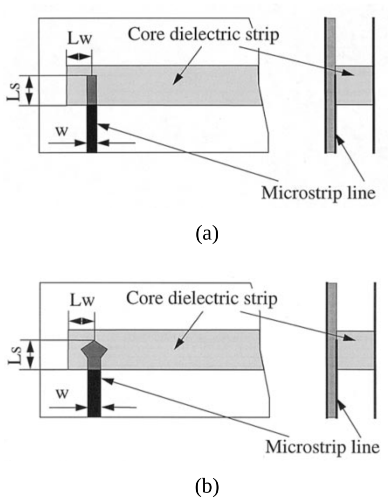

Fig. 3. Straightforward arrangement of the microstrip line to the unbalanced NRD-guide transition/balun with geometrical details. (a) Basic coupling section. (b) Modified coupling section with potential improvement of performance.

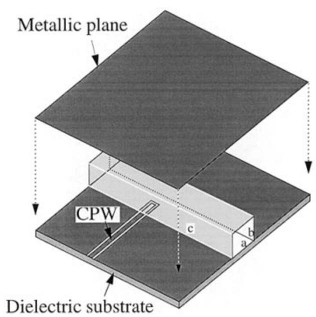

Fig. 4. Proposed integration scheme of an NRD-guide with CPW. The NRD-guide is surface mounted on one of the uniplanar CPW ground planes.

magnetic coupling is used via an aperture, which is subject to a potential resonance. In the present case, the coupling is made through the direct line-to-guide contact that has a strong magnetic coupling. This transition is expected to yield satisfactory transmission characteristics between the two dissimilar structures over a broad bandwidth.

B. Co-Layered Integration of Surface-Mounted NRD-Guide with CPW

1) New Scheme of Integration: Fig. 4 presents the proposed scheme of integrating an NRD-guide with a CPW structure. In this case, the NRD-guide is surface mounted on the uniplanar ground plane of the CPW in a straightforward manner, and the uniplanar ground plane also serves as one of the parallel plates for the NRD-guide. Therefore, the original NRD-guide geometry is perfectly preserved. This new scheme is especially useful for MMIC's and multilayered IC's.

The significant difference between the proposed integration/interconnect technique and the previous version of the hybrid NRD-guide/CPW geometry [8] lies in the arrangement of planar circuit with respect to the NRD-guide. In [8], the planar circuits were inserted into the NRD-guide. While in the new scheme, the NRD-guide is integrated in the form of a direct contact and layered format with the CPW circuits. This is a simple "put and cover" procedure, which potentially provides a low-loss and low-cost solution for millimeter-wave IC's.

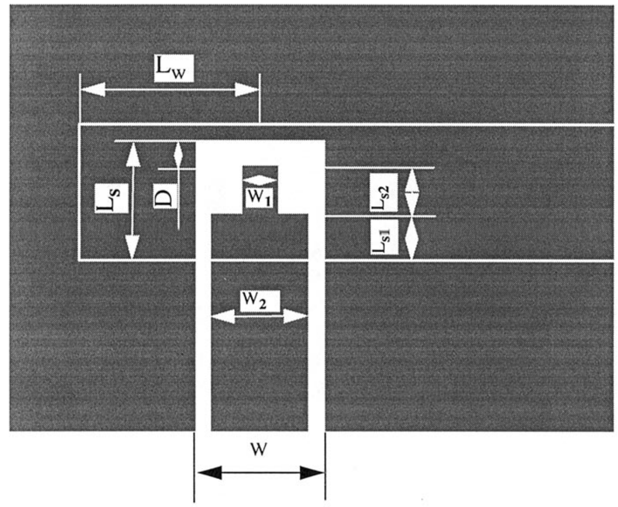

Fig. 5. Graphical sketch of an improved integration scheme with geometrical parameters for the CPW-to-NRD-guide transitions/baluns.

2) Design of CPW-to-Surface-Mounted NRD-Guide Transition/Balun: In this study, the CPW and surface-mounted NRD-guide are made of a 10-mil Duroid (Rogers) substrate ($\varepsilon_r = 2.94$) and a TMM6 (Rogers) dielectric block ($\varepsilon_r = 6$), respectively. In the similar manner, the core dielectric strip of the NRD-guide is orthogonal in space with respect to the CPW in order to excite the LSM_{01} mode. As illustrated in Fig. 5, the distance from the open end of the NRD-guide to the center of the CPW (the open-end position of the NRD-guide) is L_w. In our case studies, a CPW step discontinuity is utilized in the design to achieve a better coupling between the two structures. The penetration depth of the CPW end into the core dielectric strip is L_s. The CPW end dimensions as denoted by $L_{s1}, L_{s2}, W_1, W_2, W$, and D are also critical in exciting the wanted LSM_{01} mode in the NRD-guide and in obtaining good transmission properties between the two dissimilar structures.

III. Preliminary Experiments and Measured Results

It is difficult to design the proposed transitions/baluns in a very neat way because they involve the complex 3-D planar/nonplanar geometry. The proposed structures may be modeled with full-wave electromagnetic simulators, but such modeling tasks are usually tedious to come up with optimized design results. In our concept proof experiments, the transitions/baluns are first simulated with those electromagnetic simulators in order to gain certain insight into their electrical properties. To verify the new concept of hybrid integration and interconnect techniques, several transitions are fabricated in the Ka-band, and measured with an HP8510C vector network analyzer (VNA). Note that a low-cost rough mechanic fabrication was deployed for our experimental samples in the laboratories and tolerance errors are, of course, inevitable with regards to the designed dimensions. In any case, our objectives are to experimentally demonstrate and prove the proposed new concept. Properties of an unbalanced NRD-guide bend are also experimentally studied to show its low-radiative or nonradiative features. A thru-reflect-line (TRL)

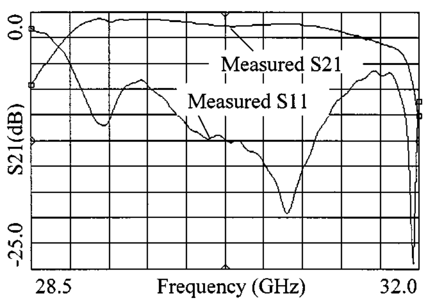

Fig. 6. In this experiment, measured insertion and return losses of a back-to-back experimental arrangement of two microstrip line-to-unbalanced NRD-guide transitions/baluns and the length of the unbalanced NRD-guide is 620 mil.

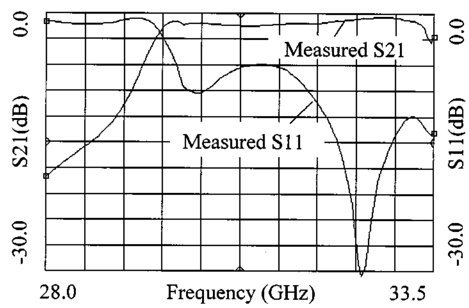

Fig. 7. Measured frequency response of the insertion and return losses of a back-to-back experimental arrangement that consists of two microstrip line-to-unbalanced NRD-guide transitions, and the length of the unbalanced NRD-guide is 500 mil.

calibration technique is applied in the measurements, and the standards are fabricated with the same substrate as used for the planar circuits.

A. Back-to-Back Transition/Balun of Microstrip to Unbalanced NRD-Guide

To begin with, a back-to-back arrangement of Fig. 2(b) with two identical transitions/baluns is considered that involves two separate microstrip lines interconnected via an unbalanced NRD-guide. In this way, the input and output remains in the form of the microstrip line that can easily be used in connection with the VNA for measurements. As our first experimental sample, the core NRD-guide is designed with dimensions of its cross section $a \times b = 158 \times 138$ and length $c = 620$ (unit = mil). Measured results of this arranged structure are shown in Fig. 6 for its insertion and return losses. It can be found that the measured results for the insertion loss present a relatively flat and wide frequency response, indicating a broad-band feature with a low transmission loss. In our experiments, the insertion loss is observed to be less than 1.2 dB for the complete block that consists of the two back-to-back transitions and interconnecting lines over the effective frequency range. Such attractive properties come from the strong magnetic coupling between the two direct-contact structures, as mentioned in the previous section. On the other hand, the return loss is reasonably good, except a small rise around 29.4 GHz, which can be reduced with further studies.

Our second experimental sample is made of a core NRD-guide with its cross-section dimensions $a \times b = 150 \times 138$ and length $c = 500$ (unit = mil). Measured insertion and return losses of its back-to-back structure are given in Fig. 7, the best insertion loss in the frequency range is about 0.5 dB obtained around 32.5 GHz, and the return loss is better than 20 dB, thereby showing very promising characteristics at millimeter-wave frequencies. Similar frequency responses are observed in Fig. 7 with reference to Fig. 6, except that the low end of the effective frequency band is pushed up. This is because the cutoff frequency of the unbalanced NRD-guide is effectively modified with the change in dimension.

B. Unbalanced NRD-Guide Interconnect

Interconnects of planar circuits at millimeter-wave frequencies can be realized by the proposed unbalanced NRD-guide

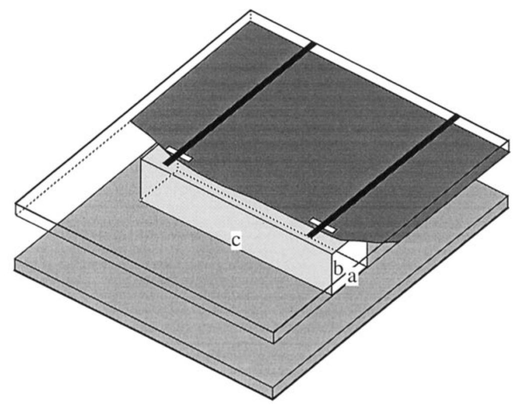

Fig. 8. Interconnect and integration demonstrations of two electrically separate microstrip lines on the same planar substrate using an unbalanced NRD-guide. The microstrip lines are coupled to the unbalanced NRD-guide via two slot apertures, as reported in [5].

with a "put and cover" procedure. To illustrate this proposal, a special back-to-back interconnect, as sketched in Fig. 8, is fabricated and measured for two microstrip lines on the top of a TMM3 (Rogers) substrate of 15 mil ($\varepsilon_r = 3.27$) that are connected through an unbalanced NRD-guide. In this case, the scheme is achieved with aperture-based feed-through couplings of the microstrip lines to the NRD-guide, similar to our previous hybrid integration technique, except the use of an unbalanced NRD-guide. In this case, the core NRD-guide is made of Polystyrene with dimensions of its cross section $a \times b = 158 \times 138$ and length $c = 620$ (unit = mil). Measured results are displayed in Fig. 9, also showing good characteristics, and the transmission loss is slightly higher, but the frequency response of the return loss looks satisfactory over a wider bandwidth of frequency.

The removal of the unbalanced NRD-guide will obviously disconnect the two lines. This useful interconnect may be made at low cost and it also may be more convenient than wire bonding and other pragmatic approaches at millimeter-wave frequencies. This points to the convergence of the two usually separate high-frequency design aspects: integration and interconnects that are, in fact, consistent with each other.

C. Unbalanced NRD-Guide Bend

To show potential radiation and leakage losses due to the use of an unbalanced NRD-guide, one experiment is made for two

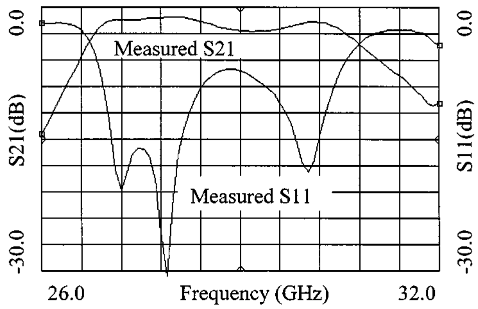

Fig. 9. Measured frequency response of the insertion and return losses of two interconnected microstrip lines (see Fig. 8) via a length of a 620-mil unbalanced NRD-guide.

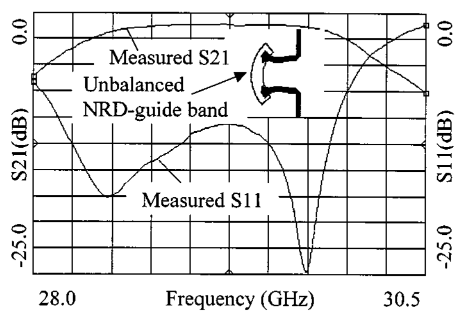

Fig. 10. Measured insertion and return losses of the complete experimental building block for two interconnected microstrip lines that involves the depicted topology of a length of a 90° unbalanced NRD-guide bend. In this experiment, the microstrip lines are in direct contact with the unbalanced NRD-guide, as shown in Fig. 2(b).

microstrip lines that are connected with each other via an unbalanced NRD-guide bend, as shown in Fig. 10. The two transitions are designed with reference to Fig. 3. This bend spans a sectorial angle of 90° and its radius of curvature is 500 mil. Dimensions of its cross section are selected as $a \times b = 158 \times 138$ (unit = mil). Measured results are shown in Fig. 10 for the insertion and return losses over the bandwidth of interest. Compared to our first two examples, which are made of the similar, but a straight unbalanced NRD-guide, the results of Fig. 10 indicate that any potential leakage loss due to the bend is truly negligible in this example. If the leakage is present in the structure, the resulting loss would be much smaller than its conductor counterpart if the NRD-guide is replaced by a curved microstrip line judging from Ka-band loss parameters known in the literature for the microstrip line.

D. Back-to-Back Transition/Balun of CPW to Surface-Mounted NRD-Guide

Our final experiment showcases a back-to-back arrangement of two CPW lines that are interconnected via a length of a surface-mounted NRD-guide. In this way, the input and output remains in the form of CPW that can easily be used in connection with a VNA for our measurements. The CPW lines and the surface-mounted NRD-guide are made of a 10-mil Duroid (Rogers) substrate ($\varepsilon_r = 2.94$) and TMM6 (Rogers) dielectric block ($\varepsilon_r = 6$), respectively. The CPW end step is designed with $L_{s1} = 30$, $L_{s2} = 30$, $D = 15$, $W_1 = 12$, $W_2 = 58$, and $W = 70$ (unit = mil) with reference to Fig. 5. Two NRD-guides

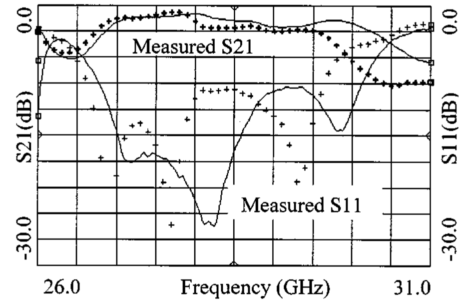

Fig. 11. Measured insertion and return losses of two back-to-back experimental arrangements that consist of two CPW-to-surface-mounted NRD-guide transitions/baluns with the lengths of the unbalanced NRD-guide are chosen as 580 mil (solid lines) and 600 mil ("+" lines), respectively. The improved coupling section as shown in Fig. 5 is used in the experiments with the parameters: $L_{s1} = 30$, $L_{s2} = 30$, $D = 15$, $W_1 = 12$, $W_2 = 58$, and $W = 70$ (unit = mil).

are designed and fabricated with dimensions of the same cross section $a \times b = 100 \times 150$ and with two different length $c = 580$, and $c = 600$ (unit = mil), respectively. Measured results are presented in Fig. 11 for the complete experimental block consisting of the two back-to-back transitions/baluns and interconnecting lines. For the 600-mil NRD-guide, it is found that the best insertion loss is about 1.0 dB obtained around 27.75 GHz, and the return loss is better than 20 dB. As for the 580-mil NRD-guide, the best insertion loss is about 1.2 dB around 28 GHz, and the return loss is also better than 20 dB. Such preliminary results, once again, demonstrate very promising characteristics of the proposed schemes for millimeter-wave applications.

IV. Conclusion

In this paper, a concept of hybrid integration and interconnects is presented for the design of millimeter-wave IC's. The proposed concept consists of two distinct schemes that involve the hybrid integration of an NRD-guide in direct-contact coupling with microstrip and CPW circuits. In essence, the first scheme makes use of an NRD-guide deposited on a relatively thin dielectric substrate, thus forming an unbalanced NRD-guide. Co-layered microstrip circuits are designed on the same dielectric substrate. This approach is inspired by the fact that the susceptible leakage loss due to the NRD asymmetry may be very small or even completely suppressed with some adequate geometrical arrangement as compared to the conductor loss if the NRD-guide is replaced with planar lines. The second scheme is developed on the basis of a hybrid integration of the NRD-guide and CPW circuits, both of which share the same ground plane. In this case, the NRD-guide can be regarded as a surface-mounted structure on the top of the CPW, and the original geometry of the NRD-guide is well preserved with the known advantageous features.

Our preliminary experiments have firmly validated the proposed concept and also the usefulness of the new schemes, which are shown with distinct advantages. One of the most interesting and also fundamental observations in this paper is that the integration and interconnect can be unified and handled in the same manner and, in fact, they present the same design aspects. The present studies show that the proposed co-layered transitions/baluns are promising with low-signal loss between the two dissimilar structures. Further work should be done for in-depth understanding of comprehensive properties of the new schemes, which are critically important for successful design. This new concept features added advantages in our hybrid integration technology of planar circuits/NRD-guide [5] for the design of 3-D multilayered IC's and millimeter-wave MMIC's.

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