Hybrid Integration Technology of Planar Circuits and NRD-Guide for Cost-Effective Microwave and Millimeter-Wave Applications

Ke Wu, *Senior Member, IEEE,* and Liang Han

***Abstract*— An architecture called the hybrid planar/non-radiative-dielectric (NRD) waveguide integrated technology is proposed as a building block for constructing microwave and millimeter-wave circuits. This hybrid approach of integration offers a unique possibility of exploiting inherent complementary advantages of planar structures and NRD waveguides for low-cost wireless applications while eliminating the potential drawbacks associated with both dissimilar structures. Compared to the existing NRD-guide related technology, the proposed framework consists of relocated planar structures on the top and/or the bottom plates of an NRD-guide, sharing the common ground planes. Such a hybrid scheme is particularly suitable for millimeter-wave systems in which active devices can be made with the planar-line technique while passive components can be made with the NRD-guide technique. The two subsets of a complete functional system are interconnected through a class of aperture-based transitions which can be designed to have wide-band performance. In addition, the multichip module (MCM) technique is readily achieved under this proposed scheme. Experimental prototypes, including passive-component and active-device, based on the new hybrid technology presented in this paper, show that the novel hybrid technology promises to be useful in the design of future microwave and millimeter-wave circuits and systems.**

***Index Terms*— Hybrid technology, nonradiative dielectric (NRD) guide, planar circuit, transition, filter, oscillator.**

I. Introduction

THE FORECAST traffic congestion of the well-defined RF spectrum for wireless communications including local area networks (LAN's), and personal communication service (PCS) has already generated considerable interest in both microwave and millimeter-wave frequency range. In particular, the millimeter-wave transmission, unlike the RF and microwave characteristics, presents some interesting features for short-haul high-speed data links, line-of-sight LAN's, and imaging radar, as well as collision-avoidance sensor applications. These features include frequency re-use, quasi-optical propagation, and high-resolution [1]. However, any successful deployment of a wireless technology at millimeter-wave frequencies that is intended for widespread and extensive commercial applications depends on the availability of a technology having properties such as low cost, compact size, low power consumption, and mechanical rigidity. In addition to these favorable factors, it is also required that the applied technology offer low-loss signal transmission, which is essential for realizing high Q circuits.

The state-of-the-art development of commercial microwave and millimeter-wave components and systems indicates that the multilayer planar technology is able to provide a high-level modular integration platform achieving some of these stringent requirements such as low cost and compactness [2]. However, such a technology has a number of limitations in the design of high-performance millimeter-wave circuits and systems. These problems arise in a typical example of realizing a highly selective bandpass filter for which the multilayer planar technology becomes vulnerable due to high transmission loss. The active approach using negative resistance may offer a possible solution but at relatively high cost, and also potentially at the expense of sacrificing noise performance and dynamic range. It seems that to a great extent, it is difficult to simultaneously achieve the above-mentioned designated specifications under a single technology framework. This argument suggests that an appropriate hybrid scheme involving two or more technologies provides a unique possibility of obtaining all the desired features by combining the advantages of each technology while eliminating their individual inherent shortcomings. Technologies that have been used to date may be divided into two classes—namely, planar technology and nonplanar technology. The former is often related to the microwave integrated circuit (MIC), miniaturized hybrid microwave integrated circuit (MHMIC), and monolithic microwave integrated circuit (MMIC), while the latter refers more or less to the metallic waveguide, coaxial line, and dielectric waveguide. In view of its advantages and disadvantages, the nonplanar technology has been known for its complementariness with respect to its planar counterpart. Obviously, the hybrid scheme based on combined planar and nonplanar technology is more appealing.

The modular integration of a microstrip line with the metallic waveguide has been reported in [3], which was essentially related to the design of a wide-band transition between the metallic waveguide and microstrip line. Judging

Manuscript received October 1, 1996; revised February 28, 1997. This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada under a strategic grant.

K. Wu is with the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong, on leave from Poly-Grames Research Center, Department de Génie Electrique et de Génie Informatique, École Polytechnique de Montréal, Montréal, P.Q., Canada H3C 3A7.

L. Han is with the Farrinon Division, Harris Corporation, Montreal, P.Q., Canada H9B 3G4.

Publisher Item Identifier S 0018-9480(97)03918-5.

from its geometry and its compatibility with the planar circuits, the metallic waveguide is bulky and cannot provide a high-level of integration. To date, very limited information is available for building up a hybrid scheme which is operational at millimeter-wave frequencies. On the other hand, very little attention has been directed to the potential integration of a planar structure with dielectric waveguide, even though a large class of dielectric waveguides have already been proposed for millimeter-wave and submillimeter-wave applications. This is probably due to the fact that the fundamental limitation of using a dielectric waveguide lies in its severe radiation loss once circuit bends and discontinuities are encountered, which jeopardizes useful applications of the dielectric waveguide. This perception held until the invention of a nonradiative dielectric (NRD) waveguide [4]. However, the NRD-guide, like any other dielectric waveguide, presents some difficult problems when active device integration is required. It is detrimental to the development of a complete NRD-based functional system since it always requires an integration or an interconnection of active devices and passive components. Therefore, the integration and interconnection of a dielectric waveguide with other dissimilar structures also presents a very challenging problem in the use of the dielectric waveguide. This issue will be discussed in the subsequent section.

This paper proposes a new scheme that effectively integrates NRD-guide-based components with planar circuits. In this new hybrid technology, the NRD-guide is intended for use in the design of passive components while the planar geometry is primarily used to design active devices. In this way, the proposed hybrid technology inherits and combines the advantages of both the NRD-guide and the planar circuits. The integration between the two dissimilar structures is achieved by aperture coupling, which has recently been proposed by the authors [10]. This paper will emphasize the electrical and mechanical performance of the proposed hybrid technology as well as its potential applications. A number of experimental prototypes including wide-band integrated transitions from microstrip-line–to–NRD-guide, a hybrid planar NRD filter, and a planar NRD oscillator will be presented and discussed. This will reveal interesting and attractive aspects of the new technology for microwave and millimeter-wave applications.

II. Technical Merit and Limitations of the NRD-Guide Technology

Before getting into the details of the proposed hybrid technology, it will be helpful to briefly discuss the technical merit and limitations of the existing NRD-guide technology. This will throw light on the motivation and background as to the basis for proposing this new hybrid technology. The NRD-guide-based technology becomes attractive for use in a variety of microwave and, in particular, millimeter-wave circuits and systems. Since its inception in 1981 [4], this technology has been used in the design and fabrication of a large class of integrated circuits and antennas which have demonstrated superior electrical performance at millimeter-wave frequencies [5]–[7]. Therefore, the NRD-guide technology has received considerable attention in the microwave research community and commercial sectors. Essentially, the NRD-guide, as shown in Fig. 1, distinguishes itself from other dielectric waveguides by the fact that its radiation losses due to circuit discontinuities and bends along the propagation path can be almost completely suppressed. Compared to planar structures, the NRD-guide offers low transmission loss and low cost. It is able to form an integrated structure of multiple circuits which are sandwiched between two parallel metallic plates. In addition, the NRD-guide can be used to design a class of leaky-wave millimeter-wave antennas [8] and unidirectional dielectric radiators (UDR's) [9].

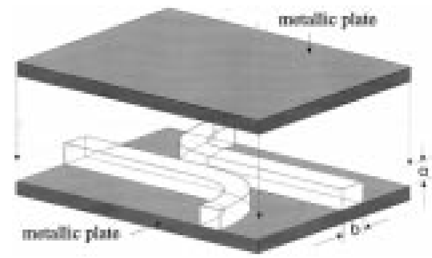


Fig. 1. 3-D view of an NRD-guide component having a dielectric strip characterized by the height of a, which is slightly smaller than half of a free-space wavelength and the width of b, which is essentially determined by the required monomode bandwidth.

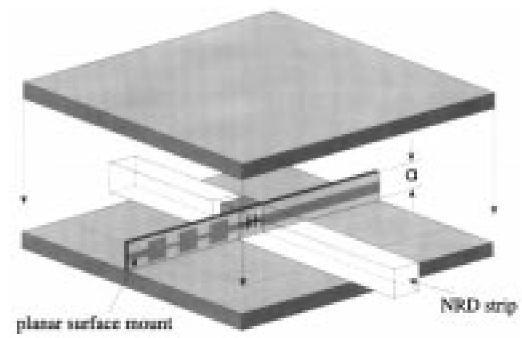


Fig. 2. Illustration of the conventional integration technique of an active device with the NRD-guide through a planar surface mount, which is inserted and coupled with the NRD-guide by an appropriate matching network involving an air-gap and a high-permittivity dielectric sheet.

Over the past years, a number of two-terminal active devices have already been used in the design of NRD-guide active circuits. Most of these devices are based upon the beam-lead diodes [7] that may be inserted into the NRD's dielectric strip through a piece of planar surface mount. The RF, microwave, or millimeter-wave signals are usually directed from the NRD to the planar circuit on which the active devices are incorporated. However, effective coupling from the NRD to the planar circuits requires an additional effort since the impedance mismatch for this hybrid geometry is a severe problem. This is usually done by adding a thin dielectric sheet having an appropriate high permittivity in conjunction with a certain dimensioned air-gap between the NRD-guide and the planar mount. This is schematically illustrated by Fig. 2, in which a two-terminal diode serves as the power detector. If not properly designed, the mismatch between these circuits may jeopardize the electrical performance. The most serious

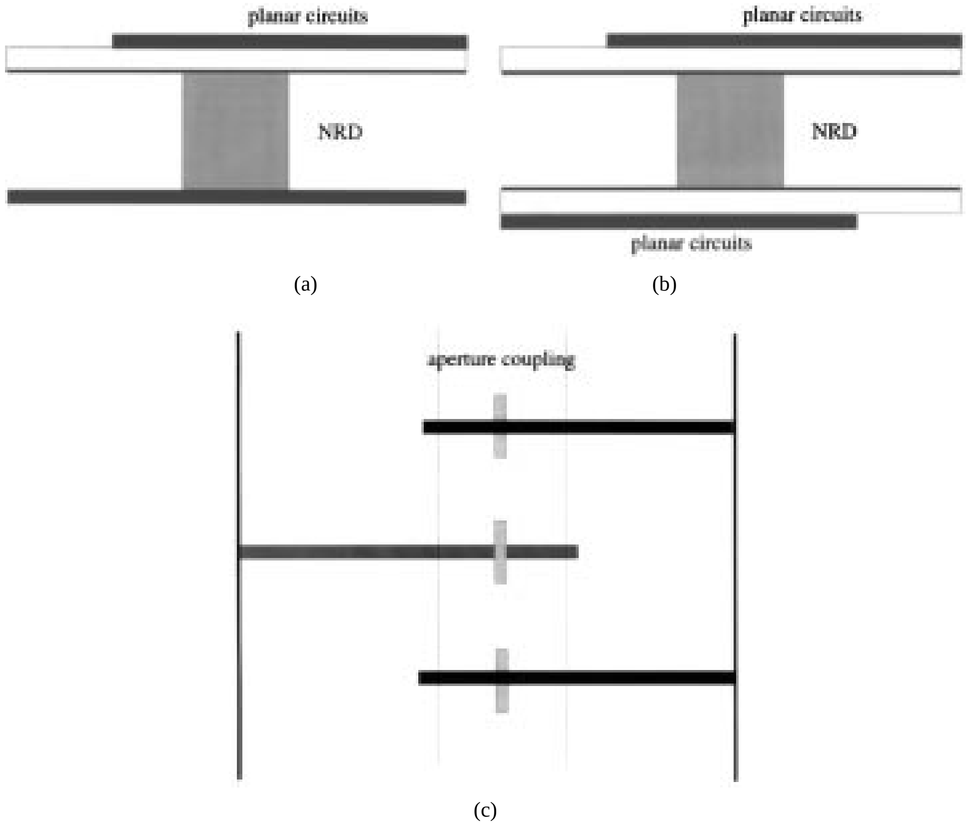


Fig. 3. Schematic illustration of the proposed hybrid planar/NRD-guide integration technology. (a) Cross section of a unilateral aperture microstrip-line–to–NRD-guide coupling scheme. (b) Cross section of a bilateral aperture microstrip-line–to–NRD-guide coupling scheme. (c) Longitudinal sectional view of multiple-aperture microstrip-line–to–NRD-guide coupling scheme.

problem is the fundamental limit of the spacing between the two metallic plates, thereby restricting the allowable cross-sectional surface or lateral dimension of the planar mount because the spacing should be smaller than half of a free-space wavelength. This may lead to some extremely difficult situations as the operating frequency increases, even if only two-terminal devices are considered. In most practical applications, three-terminal devices such as FET's, high electron-mobility transistors (HEMT's), and heterojunction bipolar transistors (HBT's) are essential in the design of oscillators and amplifiers, as well as other active circuits. However, it may be very difficult, or even impossible, to integrate these active devices into a planar circuit mount that physically fits within the required spacing of the NRD-guide. This is particularly true when packaged devices are used. For both packaged and unpackaged devices, the surface contact between the devices and the NRD-guides or the matching dielectric sheet is not always easy to achieve and is susceptible to air-gaps. The air-gap under this circumstance may be responsible for potential power leakage, mode conversion, and impedance mismatching. In addition, this integration scheme may be unsuitable for a large-scale batch production, thereby leading to a relatively high cost for commercial applications. Consequently, an alternative technique for effective integration of active devices with the NRD-guide is desired.

It has been recognized that planar structures are always suitable for integration with active devices regardless of a two- or three-terminal topology. The planar circuits may be in the form of multilayered microstrip lines or coplanar waveguides or even slot lines. At millimeter-wave frequencies, these lines may exhibit a prohibitive transmission loss that presents one of the fundamental limits in the design of circuits and antennas—in particular, passive circuits and antennas. The NRD-guide structure and performance are known to be complementary with the planar line in considering a hybrid technology for a functional millimeter-wave system. If coherently designed, both technologies offer their best electrical performance while the fundamental limits or inherent disadvantages of each technology can be effectively eliminated or removed. A new class of hybrid circuits can be proposed and developed which may offer unmatched and potentially low-cost performance.

III. Integration of Hybrid NRD-Guide and Planar Structures

On the basis of the above motivation, a new proposal for integration between the NRD-guide and planar circuits has been made to eliminate the underlying disadvantages of the two building blocks at millimeter-wave frequencies while their technical benefits can be maintained. Fig. 3 shows a general view of the proposed hybrid NRD/planar technology using a series of integrated transitions which connect the planar structure coherently with the NRD-guide. The planar structure may be in the form of a microstrip line, coplanar

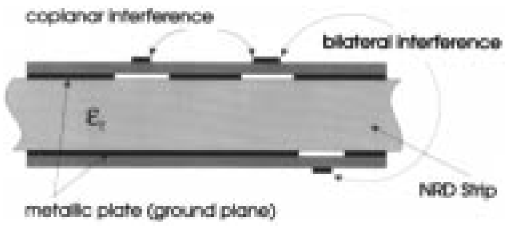


Fig. 4. Graphic representation of the interference reduction scheme described by coplanar interference and bilateral interference between two groups of planar circuits under the proposed hybrid integration technique.

waveguide, or even slot line. In Fig. 3, only the microstrip line is considered for the following discussion, although alternative planar structures can be used in the design and fabrication of such transitions. In this case, it can be seen that the integrated transition of microstrip-line–to–NRD-guide is made through magnetic aperture coupling. The microstrip line is placed in the perpendicular direction to the dielectric strip of the NRD-guide. The length of the open-ended microstrip, with respect to the coupling rectangular slot, is crucial in the design of good quality transitions. The microstrip line can be relocated on either side of the parallel metallic plates of the NRD-guide. In this way, the microstrip line shares the common ground plane with the NRD-guide which is actually one of the parallel metallic plates. The coupling aperture is made in the ground plane (the parallel plate).

Obviously, a number of microstrip lines can be attached on both sides of the NRD-guide simultaneously. This consideration gives rise to some interesting features of the proposed hybrid technology. First, both sides can be effectively used so that a complete integrated system can be designed to be as compact as possible and no space is wasted. The proposed hybrid technology can also be used to suppress, partially or completely, unwanted effects such as cross-talk, by placing the circuits or groups of concern on opposite sides of the NRD-guide. The circuits can be interconnected through an NRD-guide bandpass filter or an appropriate direct transition, or there may be no electromagnetic interconnection between them at all. To name an example, if a complete transceiver based on the proposed hybrid technology is designed and fabricated, isolation between the transmitting and receiving circuits can be easily achieved by mounting the circuits on opposite sides of the NRD-guide. At the same time, they are interconnected via the NRD-guide components. In other words, they are able to share the same passive components such as resonators and filters. In this way, any potential spurious coupling and parasitic interference can be reduced to extremely low levels. Fig. 4 clearly shows such a generic arrangement in which two planar circuits can be located in the same side or on the two opposite sides in which the parasitic interference may be significantly different. This proposed hybrid technology offers a compact, self-packaged structure to mount the required electronics. Obviously, multilayered planar/NRD topologies can be developed and used to achieve a much higher level of circuit integration.

The proposed hybrid technology completely removes the space constraint imposed by the existing hybrid scheme, and allows for the design of active and passive circuits in a very flexible way with added attractive features such as the above-mentioned space-savings and interference reduction. The passive components made of the NRD-guide offer unmatched performance such as high Q, low-loss transmission, radiationless, and potential cost effectiveness. The advantages of the planar structures are exploited for the design and realization of two- or three-terminal-based active devices such as easy integration and use of M(H)MIC's. To some extent, a multichip module (MCM) can be used in the framework of such an architecture. Further, the proposed hybrid planar/NRD technology can also be extended to build up *multilayered NRD* hybrid geometry with surface-mounted MCM's. Therefore, this new technology presents a high-level integration involving dielectric waveguide and planar circuits, which may be in the form of MIC's, MHMIC's, and MMIC's.

The integrated transition between the NRD-guide and planar structure is the key to a successful application of this new hybrid technology. The preliminary design issue and electrical performance have been presented in [10] for the transitions between the NRD-guide and microstrip line with modeling and experimental results. The proposed hybrid technology is potentially low cost since the basic design of the NRD-guide-based components are related to a series of mechanic fabrications and assembling of integrated and discrete devices and components. As such, this unique solution allows for a complete integration of T/R modules with antennas within a single framework.

It is recognized that an aperture-coupled hybrid scheme involving dielectric waveguide and planar structure has been proposed, such as recent work on analysis and design of aperture-coupled microstrip patch antennas and arrays fed by image dielectric waveguide [14]. The fundamental problem of this hybrid scheme is that the image dielectric waveguide cannot be used to design high-quality components and finds very limited applications such as the use of feeding line for which no line discontinuities are involved. Otherwise, a high radiation loss of an image dielectric waveguide component will be inevitable. In addition, the operating mode between the NRD-guide and the image dielectric waveguide is completely different and the nature of the aperture coupling is also different. These arguments pinpoint the novelty and a potential wide range of applications of the proposed hybrid technology.

IV. Experimental Demonstration of the Proposed Hybrid Technology

In this section, the usefulness and the potential applications of the proposed hybrid technology are shown through three distinct experimental examples encompassing passive and active circuits as follows:

1) NRD-guide–to–microstrip transition;
2) planar NRD-guide bandpass filter;
3) planar NRD oscillator.

Note that these preliminary experimental examples do not present optimized electrical performance but are essentially designed to showcase the proposed new scheme. It is also

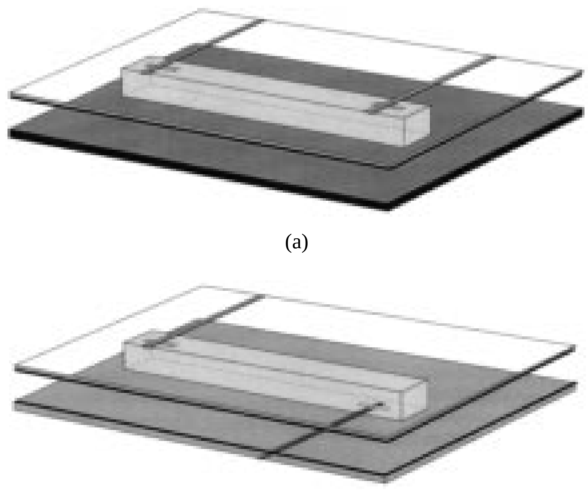


Fig. 5. Transparent view of two interconnected transitions of microstrip-line–to–NRD-guide though a length of NRD-guide. (a) Microstrip lines are located on the same side of one of the NRD's parallel plates. (b) Microstrip lines are located on opposite sides of the parallel plates of the NRD-guide.

not of interest in this paper to detail the design procedures in connection with the following examples since this paper's principal objective is to showcase this new hybrid technology.

A. NRD-Guide–to–Microstrip Transition

A similar microstrip-line–to–NRD-guide transition (as illustrated in Fig. 5) was previously proposed by the authors' research group and used to feed a UDR [11]. However, the transition used in this case [11] operates within a narrow bandwidth which is different from that of circuits for which wide-band performance may be required. Therefore, the topology and design of such a wide-band transition are much more involved. Note that the transition in Fig. 5 is different from that shown in Fig. 3, in which the NRD-guide simply becomes an underpassing transmission line with respect to the microstrip line. To name an application example, in the case of Fig. 3, the microstrip line may be used to design a power detector for probing signal transmission of the NRD-guide. Fig. 5 presents two different topologies which may be arranged for different interconnections. Once again, it is shown that this design allows a degree of freedom for locating planar circuits on either ground plane for potentially achieving the maximum electromagnetic isolation. As such, all the upper and lower spaces may be used and the complete system can be made very compact without losing the stringent requirement of isolation.

The design of microstrip-line–to–NRD-guide transition is actually focused on the impedance matching between two dissimilar structures which are coupled to each other through a rectangular aperture. An appropriate choice of permittivity of the NRD dielectric strip is critical together with an adequate length of the open-ended microstrip line. To verify electrical performance of the proposed transition, an experimental prototype is made which uses two identical microstrip-line–to–NRD-guide transitions, which are interconnected

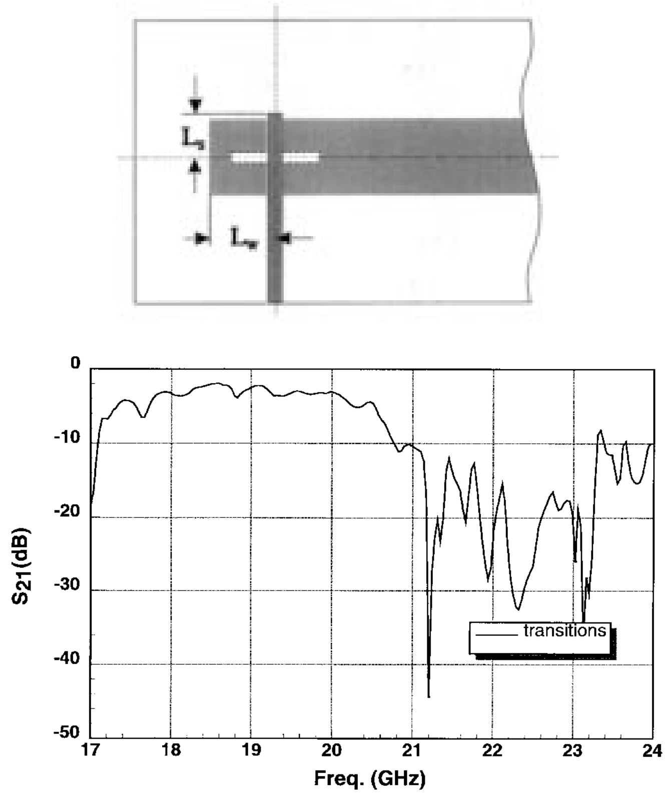


Fig. 6. Measured performance of the complete design example as shown in Fig. 5(a) with two identical microstrip–to–NRD transitions separated by a length of NRD-guide. Frequency response of Fig. 5(b) is nearly identical to that of Fig. 5(a).

through an NRD-guide terminated with two open ends having a length of 82 mm. The distance between the two microstrip feed lines is 76.42 mm and they are fabricated on a 60 $\times$ 98 mm^2 substrate (RT/Duroid 5880, $\varepsilon_r = 2.3$) with a thickness of 20 mil. The line impedance of 50 Ω is designed with a strip width of 1.53 mm. The NRD-guide is made of a rectangular dielectric strip (Rogers TMM -3, $\varepsilon_r = 3.27$) and designed to operate around 20 GHz with $a = 6.1$ mm and $b = 6.5$ mm. The coupling aperture on the common ground plane is a narrow rectangular slot with dimensions of 7.5 $\times$ 0.5 mm^2. To approximately predict the electrical performance, a simple modeling and design technique was developed and used in this paper. This technique is based on equivalent waveguide models and small aperture theory, which has been detailed in [10]. Note that the developed approximate modeling technique may not be accurate enough to predict electrical characteristics of transitions having a larger aperture or a stronger coupling, since the analytical equations used in the modeling are valid only for small aperture. Therefore, this paper's design cannot be extended beyond a certain limit. Fig. 6 shows measurement results for the designed microstrip-line–NRD-microstrip line as shown in Fig. 5(a), which operates at frequencies from 17.5 GHz to 20.5 GHz with 15% effective bandwidth. This coincides with about the same bandwidth as the operational monomode bandwidth of the NRD-guide based on this paper's design. The losses of the two microstrip feeding lines that are not calibrated out

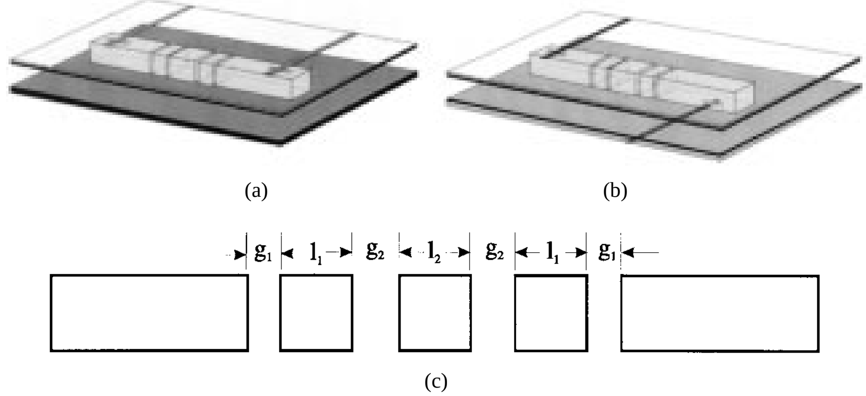


Fig. 7. Structure of a multipole bandpass NRD-guide filter with two microstrip-line–to–NRD-guide transitions. (a) Microstrip lines are located on the same side of one of the NRD's parallel plates. (b) Microstrip lines are located on opposite sides of parallel plates of the NRD-guide. (c) Symmetrical three-pole filter with parameters of structure: $g_1 = 3.02$ mm, $l_1 = 4.81$ mm, $g_2 = 6.82$ mm, $l_2 = 4.83$ mm.

are included in the measurement results and the transitions are not optimized. These losses can be attributed to radiation, impedance mismatching, ohmic, and dielectric losses. The best insertion loss for the complete circuit is observed with less than 3.5 dB over the 15% bandwidth at the center frequency of 19 GHz. The observed in-band ripple of frequency response in Fig. 6 indicates that there is a problem of internal impedance mismatching of the two transitions. It can be expected that the insertion loss and flatness within the effective bandwidth can be significantly improved in future work. These preliminary results are encouraging, considering the fact that the structure is not yet optimized and the losses of the two connection lines are not removed from the measurement.

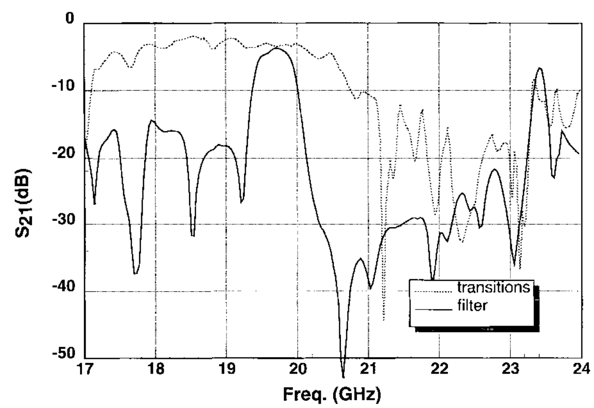


Fig. 8. Measured frequency response of a three-pole bandpass filter with the designed topology as show in Fig. 7(a), which is overlapped with the measurement results of the through transitions.

B. Hybrid Planar/NRD Bandpass Filter

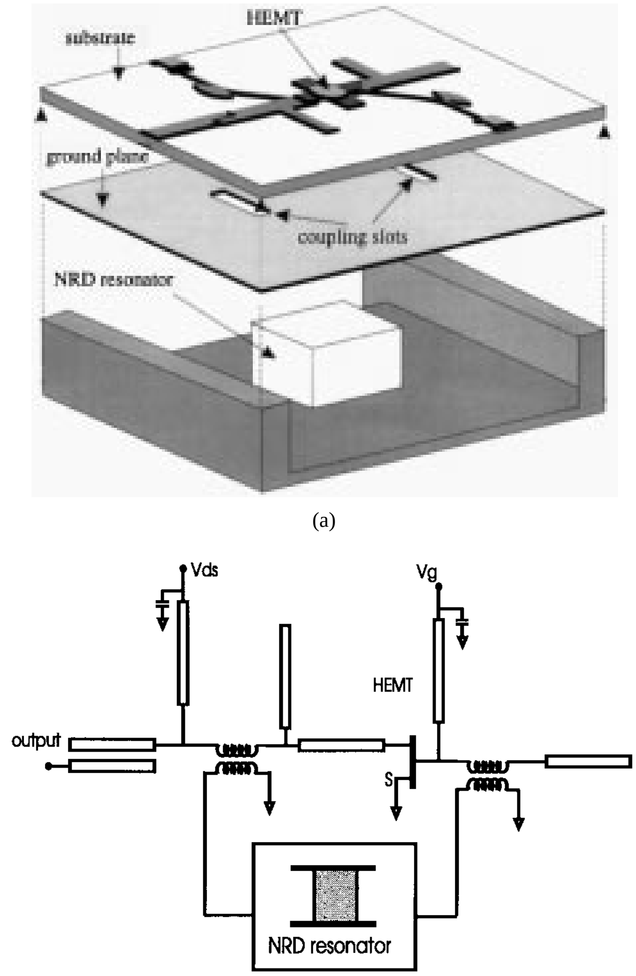
Fig. 7 demonstrates a design of two identical NRD-guide bandpass filters using the two integrated transitions of microstrip-line–to–NRD-guide. The two filters, having the same topology, present two different arrangements for the input and the output which may be located either on the same side or on the two opposite sides. Apart from the design quality of the two transitions between the microstrip lines and NRD-guide, it can be seen that electrical performance of the filter is mainly determined by the NRD-guide, but both its input and output are in the form of the microstrip line. Therefore, this hybrid technology proves itself useful for millimeter-wave applications where it may be difficult or even impossible to design a high Q bandpass filter only with a microstrip line unless expensive superconducting technology is used. In this paper's filter design, the same structural and electrical parameters of the NRD-guide and the microstrip line presented in the previous section are used. The sizes related to the NRD resonators and gaps are detailed in the caption of Fig. 7(c). The measurement results are shown in Fig. 8 for this paper's design example of a three-pole bandpass filter working at 19.65 GHz with a 2% bandwidth as shown in Fig. 7(a). Note that the experimental results of Fig. 7(b) are essentially identical to those of Fig. 7(a), which is not shown in Fig. 8. Clearly, the overlapped measurement curves of the complete transmission circuit involving the two transitions and the designed filter over the bandpass frequency range confirm that the NRD-guide contributes to the insertion loss at the negligible level while the two transitions and microstrip connection lines are responsible for it. It is observed in Fig. 8 that this experimental example has difficulty in providing high rejection at the lower side of the bandpass frequency. It can be attributed to a possible alignment problem and approximate positioning of the NRD resonators/guides during measurement, which may cause input/output (I/O) spurious coupling. Note that no fine mechanical fabrication was applied to this preliminary design example, which may also deteriorate circuit performance. Nevertheless, the overall frequency response is satisfactory. This may suggest that good mechanical tolerance should be considered in the fabrication process. This experimental demonstration clearly indicates that a high Q filter having a planar transmission line at the input and output with potential excellent out-of-band rejection can be realized at a low cost using the proposed hybrid technology without resorting to other sophisticated techniques. This example also stresses that, once again, the design of a quality microstrip-line–to–NRD-guide transition is the most important issue which needs to be addressed.

C. Hybrid Planar/NRD Oscillator

As the last design example of this paper's proposed hybrid technology, the authors present a new class of planar NRD oscillators, which provide an alternative design framework to the conventional oscillator. This new design is based on a unique three-dimensional (3-D) feature of the proposed hybrid technology with a relatively easy-to-make high Q NRD resonator, providing a number of attractive advantages over the conventional oscillator design. The high Q design of an oscillator at millimeter-wave frequencies may be a very challenging issue. The commonly used ceramic-based commercial dielectric resonator (DR) becomes so miniaturized that the surface mounting and post-fabrication tuning are usually very delicate. The high-permittivity DR may be expensive with respect to the overall cost. The coupling could be difficult to control by adjusting the space between the DR and transmission line (usually microstrip line) once the DR is deposited. Furthermore, in most cases, the circuit presents an asymmetrical geometry in view of the DR location over the microstrip line, which may generate some unwanted spurious radiation and other parasitic effects. The feedback of such a conventional oscillator is usually achieved by using some additional circuit which may complicate the design and even deteriorate the performance. Under the conventional planar design of the oscillator, the Q-factor of the DR is usually limited even if very high-permittivity material can be used to enhance the mode confinement. In this case, the dimension of the DR becomes extremely small.

It is the authors' intention to present this new planar NRD oscillator only as an application example of the proposed hybrid integration technology. A more detailed description was reported in [13] in connection with its technical merits and application aspects since the planar NRD oscillator itself is an interesting subject.

The proposed new oscillator based on the concept of the hybrid planar/NRD technology is shown in its transparent composite view in Fig. 9(a), together with its equivalent circuit described in Fig. 9(b). The fundamental difference between the proposed and the conventional oscillators is that the proposed structure removes the requirement of a high-permittivity resonator, which is necessary in the conventional technique. Instead of the conventional DR, an NRD resonator is located underneath the planar oscillating circuit, which are coupled to one another through one or two rectangular apertures. Thus, the NRD resonator can be made sizable (even at millimeter-wave frequencies) with a high Q factor if a low permittivity material is used. Actually, extremely low-cost, low-permittivity dielectric materials with low loss characteristics are available at millimeter-wave frequencies such as Teflon, polystyrene, and newly commercialized highly temperature-stable TMM® materials (Rogers' trademark). In view of its geometry and neat 3-D design, the structure presents a symmetry that is very useful for the reduction of radiation loss. In addition, the feedback becomes much easier to achieve with two apertures through which the input of the transistor is coupled with its output. A weak or strong coupling may be designed and adjusted even after its fabrication. This is an added attractive aspect for stabilizing the oscillating frequency and a typical example of using the proposed hybrid technology for designing low-cost and high-performance nonlinear active devices. In this paper, a standard layout design of the planar oscillating circuit is made with a thickness of 15 mil substrate (RT/Duroid 5880 and $\varepsilon_r = 2.3$) using HP-MDS software while the Teflon-based NRD resonator is designed with the authors' field-theoretical modeling tool [12]. A low-noise FHX15X GaAs packaged HEMT is used in this experiment. The dimensions of the NRD resonator are $a \times b \times c = 8.15 \times 14.03 \times 14.03$ mm^3 with $\varepsilon_r = 2.04$. The two coupling apertures have dimensions of 5×0.5 mm^2 with a spacing of 18.17 mm. The designed planar NRD oscillator works well and the measurement results around 16 GHz are presented in Fig. 10, showing that a maximum output power is 5.1 dBm at 16.19 GHz with the drain-bias voltage $V_{\rm ds} = 2.4$ V and the gate voltage $V_{\rm g} = 0$ V. The frequency of oscillation corresponds exactly to what is expected in the design. The measurement results also indicate that the frequency of oscillation is much less pronounced to the variation of the



(b)

Fig. 9. A new class of planar NRD oscillators for low-cost millimeter-wave applications (a) Composite diagram of a HEMT planar NRD oscillator with the design layout. (b) The equivalent circuit of the proposed oscillator.

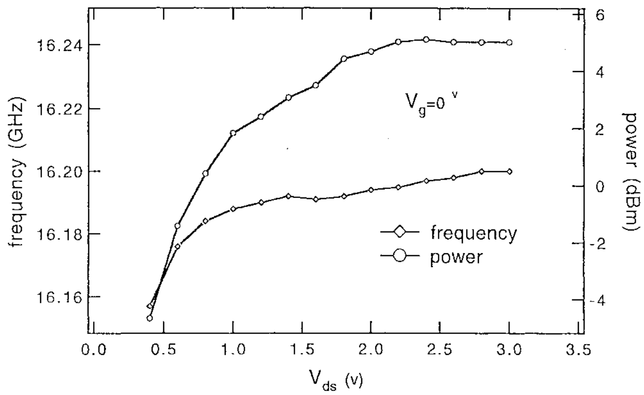


Fig. 10. Frequency of oscillation and output power of the designed planar NRD oscillator as a function of the drain-bias voltage.

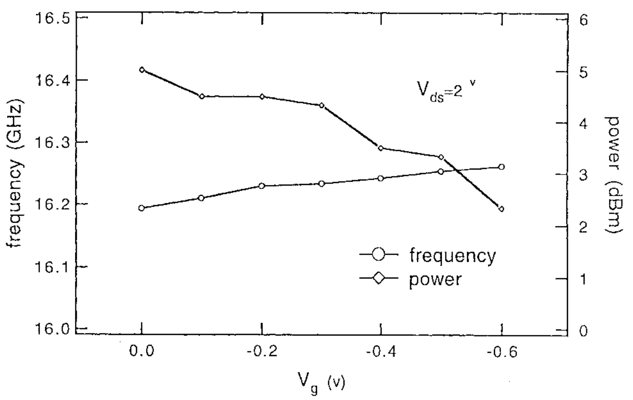


Fig. 11. Measured performance of the new planar NRD oscillator with variation of the gate-bias voltage for a fixed drain bias.

drain bias voltage once it is tuned beyond 1.0 V. However, the power can be significantly increased and approaches its maximum value with the increasing drain voltage. Fig. 11 shows the measured performance of the proposed planar NRD oscillator as the gate bias is changed for a fixed drain voltage.

Note that the NRD resonator used in this example is a simple cuboid-shaped topology having a very easy-to-visualize mode profile. Obviously, alternative NRD resonator structures can be considered in the design of a planar NRD oscillator, such as a ring resonator and air-gap coupled resonator which may provide a better Q-performance and easy control of the feedback coupling level.

V. Conclusion

This paper presents the proposal and development of a hybrid technology based on a 3-D layered design that effectively integrates planar circuits with the NRD-guide. The hybrid integrated planar/NRD technology inherits the underlying complementary advantages of both the planar structures and the NRD-guide, while the shortcomings associated with the two dissimilar topologies can be eliminated. With the above arguments and preliminary experiments, the proposed hybrid planar/NRD-guide scheme demonstrates a number of attractive features for designing passive components and active devices, which can be summarized as low cost, low-loss signal transmission, compactness, flexibility of design, and reduction of interference. In addition, the experimental prototypes presented in this paper indicate that the hybrid planar/NRD integration technique can provide a robust basis for developing a class of new circuits and devices with unmatched electrical performance. These passive and active circuits, as well as systems that are constructed with the proposed building block, offer potentially cost-effective and high-performance solutions for microwave, and in particular, millimeter-wave applications. Future extensive research and development are required to understand better technical features of this proposed hybrid scheme and also to foster its extensive use in the next generation of microwave and millimeter-wave systems.

Acknowledgment

The authors wish to express their thanks to an anonymous reviewer for his/her detailed comments and corrections made in the original manuscript which improved the readability and presentation of this paper. The useful comments from another anonymous reviewer are also very much appreciated.

References

[1] J. C. Wiltse, "Introduction and overview of millimeter waves," in *Infrared and Millimeter Wave*. New York: Academic, vol. 4, ch. 1, pp. 1–21, 1981.
[2] H. H. Meinel, "Commercial applications of millimeter-wave history, present status, and future trends," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1639–1653, July 1995.
[3] W. Grabherr, B. Huder, and W. Menzel, "Microstrip to waveguide transition compatible with mm-wave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1842–1843, July 1995.
[4] T. Yoneyama, "Nonradiative dielectric waveguide for millimeter-wave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 1188–1192, Nov. 1981.
[5] ——, "Nonradiative dielectric waveguide," in *Infrared and Millimeter Wave*. New York: Academic, vol. 11, ch. 2, pp. 61–98, 1984.
[6] ——, "Recent development in NRD-guide technology," *Ann. Télécommun.*, vol. 47, nos. 11–12, pp. 508–514, 1992.
[7] F. Furoki and T. Yoneyama, "Nonradiative dielectric waveguide circuit components using beam-lead diodes," *Electronics and Communications in Japan*, vol. 73, no. 9, pt. 2, pp. 35–40, 1990.
[8] K. Maamria, T. Wagatsuma, and T. Yoneyama, "Leaky NRD Guide as a feeder for microwave planar antennas," *IEEE Trans. Antennas Propagat.*, vol. 41, pp. 1680–1686, Dec. 1993.
[9] K. Wu, J. Li, and R. G. Bosisio, "A low-loss unidirectional dielectric radiator (UDR) for antenna and space power combining circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 339–341, Feb. 1994.
[10] L. Han, K. Wu, and R. G. Bosisio, "An integrated transition of microwave to nonradiative dielectric waveguide for microwave and millimeter-wave circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1091–1096, July 1996.
[11] H. An, K. Wu, and R. G. Bosisio, "Microstrip line excitation of unidirectional dielectric radiator (UDR) with aperture coupling," in *Asia-Pacific Microwave Conf. Proc.*, Tokyo, Japan, Dec. 6–9, 1994, pp. 79–82.
[12] K. Wu, "A combined efficient approach for analysis of nonradiative (NRD) waveguide components," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 672–677, Apr. 1994.
[13] K. Wu and L. Han, "Integrated planar NRD oscillator suitable for low-cost millimeter-wave applications," *IEEE Microwave Guided Wave Lett.*, vol. 6, pp. 126–128, Sept. 1996.
[14] S. Kanamaluru, M.-Y. Li, and K. Chang, "Analysis and design of aperture-coupled microstrip patch antennas and arrays fed by dielectric image line," *IEEE Trans. Antennas Propagat.*, vol. 44, pp. 964–974, July 1996.

Ke Wu (M'87–SM'92) was born in Liyand, Jiangsu Province, P.R.China He received the B.Sc. degree (with distinction) in radio engineering from Nanjing Institute of Technology (now Southeast University), Nanjing, P.R.China, and the D.E.A. degree in electronics and Ph.D. degree (with distinction) in optics, optoelectronics, and microwave engineering, from Institut National Polytechnique de Grenoble (INPG), France.

He conducted research in the Laboratoire d'Electromagnetisme, Microondes et Optoelectronics (LEMO), Grenoble, France, prior to joining the Department of Electrical and Computer Engineering at the University of Victoria, Victoria, B.C., Canada. Subsequently, he joined the Departement de genie electrique et de genie informatique at the École Polytechnique de Montréal, Montreal, P.Q., Canada, where he is now an Associate Professor. He held a 1995 Visiting Professorship sponsored jointly by the French/Quebec governments in France. He is currently a Visiting Professor at the City University of Hong Kong, Kowloon, Hong Kong. He has published over 170 refereed journal and conference papers. His main research interests include analysis and design of various microwave/millimeter-wave integrated circuits and antennas, high-speed interconnects and packaging effects, numerical methods, dielectric material characterizations, and superconducting devices. He is also interested in research and design of broad-band optoelectronic components and lightwave transmission systems with emphasis on traveling-wave electro-optic modulators, couplers, and switches.

Dr. Wu received a U.R.S.I. Young Scientist Award and the Oliver Lodge Premium from the IEE. He has served on the editorial review boards of various technical journals, including IEEE Transactions/letters (MTT, AP, MGWL) and he provides consulting services to a number of industries and government agencies. He is also the head of the FCAR Research Group, and has directed a number of international collaborative research programs. He was chairperson of the 1996 ANTEM's Publicity Committee and served as a panel member for the FCAR Grant Selection Committee (1993–1996) and the IEEE Admission and Advancement (A&A) Committee. He is currently a member of the Steering Committee for the 1997 joint IEEE AP-S/URSI International Symposium, the Technical Program Committee (TPC) for the 1997 IEEE MTT-S International Microwave Symposium, the TELSIKS'97, and the ISRAMT'97. He is also TPC vice-chairperson for the 1997 Asia-Pacific Microwave Conference.

Liang Han was born in Nanjing, P.R.China He received the B.Sc. degree in engineering from Nanjing University of Post and Telecommunications, Nanjing, P.R.China, in 1982, and the MSEE and Ph.D. degrees in engineering from Southeast University, Nanjing, P.R.China, in 1988 and 1991, respectively.

From 1991 to 1993, he conducted research in the State Key Laboratory of Millimeter-Wave, Southeast University, P.R.China During April 1993 and May 1994, he was a Research Fellow in the Royal Society Fellowship. In August 1994, he was with the Poly-Grames Research Center of Ècole Polytechnique de Montréal, Montreal, P.Q., Canada, where he was a Post-Doctoral Fellow. He is presently a Senior RF Engineer in the Farrinon Division of the Harris Corporation, Montreal, P.Q., Canada. His research interests include design and simulation of RF/microwave and millimeter-wave active and passive circuits and subsystems for wireless communication.