FACTA UNIVERSITATIS (NIŠ)
Series: Electronics and Energetics vol. 11, No.1 (1998), 1-6

HYBRID THREE–DIMENSIONAL PLANAR/NON–PLANAR CIRCUITS FOR MICROWAVE AND MILLIMETER–WAVE APPLICATIONS: THE STATE–OF–THE–ART AND CHALLENGE

Ke Wu

Abstract. The recently proposed hybrid integration technique of planar/NRD–guide circuits and the rapid progress in the development of three–dimensional (3D) MMICs as well as the micromachined high–frequency ICs based on MEMS suggest that a unified multilayered framework of integrated multifrequency multichip modules be attractive for low–cost high–performance microwave and millimeter–wave circuits and systems. This new generalized scheme makes it possible to exploit complementary distinctive advantages of various strip and slot planar structures as well as NRD–guide within a single framework. This paper reviews briefly the state–of–the–art of research activities on hybrid 3D planar and nonplanar structures for microwave and millimeter–wave ICs with emphasis on the newly proposed hybrid planar/NRD circuits. Potential challenging problems in connection with the 3D design and integration are discussed and future R&D directions are also indicated. In particular, it is suggested that hybrid multilayered scheme involving dissimilar structures can be effectively integrated in a monolithic format.

1. Introduction

There are significant worldwide interests related to the research and development of commercial and/or dual–use based microwave and in particular millimeter–wave components and systems [1] for such applications as

Manuscript received April 17, 1998.
A version of this paper was presented at the third Conference Telecommunications in Modern Satellite and Cables Services, TELSIKS'97, Niš, Yugoslavia.
The author is with the Poly–Grames Research Center, Dept. de génie électrique et de génie informatique, École Polytechnique, C. P. 6079, Succ. Centre–Ville, Montréal, Canada H3C 3A7. He holds also a visiting professorship with the Telecommunication Research Center, Department of Electronic Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong SAR, PRC.

LMDS (Local Multipoint Communication System) in the USA/Europe or LMCS (Local Multipoint Communication System) in Canada at 28 GHz or MVDS (Multichannel Video Distribution System) in Europe at 41 GHz. In Japan, the V– band (60 GHz) components and systems have been successfully explored for high-speed wireless and hybrid wireless/wireline (optical cable) systems. It is widely accepted that any successful deployment of a wireless technology at microwave and millimeter–wave frequencies intended for widespread commercial applications depends heavily on the availability of a technology having properties such as low–cost, compact–size, low-power consumption and mechanic rigidity. These broadband LMDS/LMCS/MVDS wireless applications and other millimeter-wave wireless systems such as 38 GHz PCS and 60 GHz short–haul high–speed data links as well as 94 GHz space-ground communications require definitely new technologies to address these design challenging issues.

The design of a complete wireless transceiver system is usually divided into two distinct blocks, that is, radio–frequency (RF) front–end and mixed analog/digital baseband module. The baseband block may be related to signal processing units and A/D conversion as well as carrier/signal frequency recovery process, synchronization, modulation, channelization, and etc., while the front–end part is responsible for up/down conversion units of the signal with respect to the microwave or millimeter–wave carrier frequency, which includes antenna circuits. It is obvious that the design of the two blocks is closely related to each other, judging from the system requirement.

As for broadband applications at millimeter–wave frequencies, the signal bandwidth may largely exceed 1 GHz, and thus, the baseband itself becomes a part of microwave unit. Therefore, the design of such a millimeter–wave system is much more complicated since a number of issues should be considered such as mixed digital/analog signal interconnects, low– and high–frequency packaging, co–channel interference, return–path design for interactive two–way service, fabrication and design cost effectiveness and integration degree of IC functional blocks.

Meanwhile, recent progress made in the R&D of RFICs (radio frequency ICs) indicates that multilayer planar technology may provide a high–level module integration achieving some of these stringent requirements such as low–cost and compactness as well as multifrequency and multifunction operation [1]. This is in particular true when 3D MMICs [2] and Silicon–based micromachined circuits [3, 4] have been recently demonstrated. Nevertheless, such technologies using planar conductor transmission lines may have limitations in the design of high–performance millimeter–wave circuits and systems such as the vulnerable high ohmic loss of signal transmission. This can be evidenced by the design of a narrow bandpass filter. To a great extent, it is difficult to achieve simultaneously overall required circuit performance under a single technology framework. This argument eventually suggests that an appropriate hybrid scheme involving two or more technologies provide a possibility of accomplishing all desired features by combining their advantages while each individual inherent shortcoming are eliminated. Obviously, the hybrid scheme based on combined planar and non–planar technologies is more appealing.

On the other hand, alternated multilayered planar structures have been proposed for application to compact RF and microwave circuits [5], which exploit essentially the coherent and complementary advantages of each planar topology such as CPW/slotline and microstrip/stripline. Obviously, these two different groups of structure can be designed and integrated well into a single building block with alternated dielectric layer so that the compactness and advantages of each line can be benefited.

A module integration of microstrip line with the metallic waveguide has been reported in [6], which was essentially related to the design of wideband transition between the metallic waveguide and microstrip line. A similar development has been very recently described in [7], which indicates growing interests in the hybrid technique involving MMICs and waveguide at millimeter–wave frequencies.

However, little attention has been directed to the potential integration of a planar structure with dielectric waveguide even though a large class of dielectric waveguides has already been proposed for millimeter–wave and submillimeter–wave applications. Results have been reported only for planar patch antenna fed by dielectric image line [8]. It has been known that the fundamental limitation of using a dielectric waveguide is its severe radiation loss once circuit bends and discontinuities are encountered, which jeopardizes useful applications of the dielectric waveguide. This perception holds until the invention of a nonradiative dielectric (NRD) waveguide [9].

To begin with the planar multilayered hybrid scheme, this paper reviews then briefly our research progress on this new hybrid technique related to planar circuits and NRD–guide. This is because the integration between the two dissimilar structures is achieved by an aperture coupling or a balun geometry, which presents the key to successful applications of the new technique. Particular applications are made in a straightforward manner.

In a broad sense, it can be postulated that a hybrid multilayered planar/nonplanar 3D structure can be effectively designed that supports wave propagation along both planar transmission lines and dielectric waveguides (in our case study, the NRD–guide is emphasized). Potential problems are also discussed and future directions are indicated on this particular subject.

2. Planar multilayered 3D hybrid technologies

Multilayered integration has been closely related to interconnects and packaging problems once individual circuit elements are designed and realized, which are to be assembled in a block module. It has been also shown that the multilayered integration may have provided potential solutions for some headache problems such as heating dissipation of power amplifier, MMIC antenna and high–Q channel filter. Now, there is a growing interest in the 3D design of microwave integrated circuits including the use of MMICs and Silicon–based micromachining technique [2, 3, 4] that deals with the multilayered design of circuit and devices in a hybrid and/or monolithic scheme. The 3D concept of the MMICs was initially developed from the multilayer MMICs and proposed [2] to reduce wafer circuit area and also to significantly increase its integration level. Currently, two technologies have been developed for achieving ultra-compact 3D MMICs, namely, masterslice technique [10] and folded U/I–shaped microwire technique [11]. The micromachining technique that was proposed a longtime ago can be viewed as a special application of the popular MEMS (micro–electromechanical system) for low–cost and high–performance microwave and millimeter–wave circuit and system fabrication. It may be very well suited to the design and application of integrated passive circuits and components and antennas with such attractive features as self–packaging.

Fig. 1 shows, for example, the basic structure of a typical 3D master-sliced MMIC [12] with four layers of thin polyimide films and five layers of conductors stacked on a GaAs wafer. The conductor layers are connected through metallic vias and the active devices including MIM capacitors and resistors are formed on the substrate. The most significant feature of this structure is that a ground metal layer (GND) is located in the middle of the polyimide layers and passive circuits are stacked above and below the GND. The circuits are fabricated with narrow thin–film microstrip (TFMS) lines and inverted TFMS lines. This technique has already been used to develop complete single-chip receiver and transmitter [12]. One interesting aspect of the 3D MMICs is that the ground planes can be located in different layers and different locations that may be interconnected by metallic vias. In this way, the 3D MMICs are well suited to the use of various planar transmission line topologies in the multiple layers without limitations.

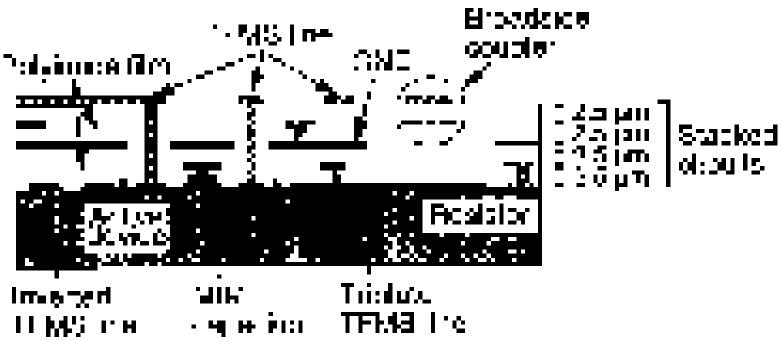


Figure 1. Basic structure of a 3D MMIC depicted in [12] for the design of a single–chip receiver and transmitter. This structure consists of 4 thin–film Polyimide layers based stacked circuits on the top of the main substrate.

On the other hand, multifrequency microstrip antennas using a 3D allumina–ceramic/polyimide multilayer dielectric substrate has also been proposed and this hybrid technique is very similar to the conventional multi–metallic layered (usually two layers) miniaturized hybrid MICs (MHMICs) except that the polyimide and MMIC chips can be deposed onto the ceramic substrate. Note that the polyimide layer has a low permittivity and provides a better design base for antennas. This technique is very useful for multilevel integration together with antenna circuits, as shown in Fig. 2 [13].

In parallel to the development of 3D MMICs, the use of Silicon–based micromachining technique has received a significant attention for fabricating microwave and millimeter–wave circuits [3,4]. This technique allows to develop a low–cost miniaturized membrane–related planar and waveguide structures and it is suitable for the design of complicated 3D structures as illustrated in Fig. 3 [14] which is a recently proposed high–Q filter structure. Actually, the micromachined structures present more or less 3D features because of the MEMS fabrication procedures. Now, the multilayer technique has been widely used in the high–speed circuit interconnects and packaging which are directly related to the mixed digital/analog design and multifrequency and multifunctional modules. In any case, vias and aperture–coupled as well as flip–chip topologies are used to interconnect the dissimilar structures.

Oriented also in the same direction, a technique of designing alternated multilayered circuit has recently been presented in [5] using a hybrid topology of CPW/slotline and microstrip/stripline. The circuit geometry has been already used in analysis and design of microwave integrated circuits.

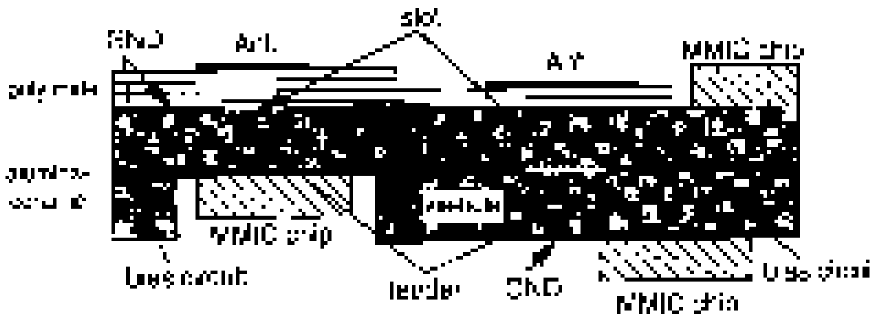


Figure 2. Illustration of a 3D multilayered hybrid ICs including integrated passive or active antennas with MMICs. In this example, an active antenna is made on the low–permittivity Polyimide layers.

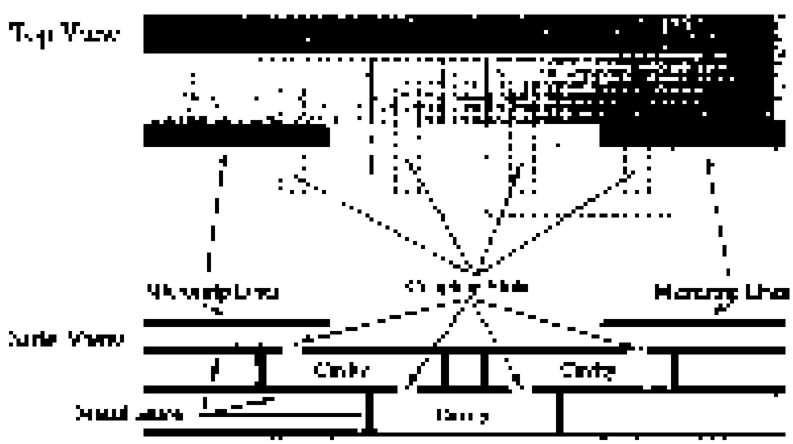


Figure 3. The recent proposal of a 3D multilayered bandpass filter structure using the micromachining technology. In this example, three high–Q microcavities are formed to design a three–poles filter.

Nevertheless, it receives little attention for the systematic inherent advantages of constructing a multilayered structure for compact applications. Using the complementary structural property of the two structure groups in view of guided–wave scheme as shown in Fig. 4, the CPW/slotline and microstrip/stripline are alternately located at different dielectric planes such that the microstrip/stripline share the same ground planes as its vertically adjacent CPW/slotline. In this way, the microstrip/stripline may become much less dispersive compared to their suspended or normal grounded microstrip counterpart while the CPW/slotline present a geometry of bounded two–layered superstrate and substrate.

Obviously, the use of a CPW or a modified CPW such as elevated CPW in the design of 3D multilayered structure provide a wide range of impedance that is vital for some joint passive and active circuit design. This can be well reflected in the design of some low–impedance active devices, which require a broadband impedance matching network. In addition, the CPW is well suited for hybrid integration of active devices such as series and parallel surface mounts of active device. However, the basic problem with the CPW is that expensive and difficult–to–characterize air–bridge or underpass is usually required to prevent guided-wave from the mode conversion or modal leakage. Using the 3D multiple layers, it is possible to design some CPW with a limited extent of co-ground planes that are turned into a new class of lines called coplanar stripline (CPS). The CPS can be generally designed as asymmetric line that shares the same advantageous feature with a CPW but may remove the requirement of air–bridge if the design is made in an adequate way. So far, very limited design guidelines are available for this new structure.

With consideration of the design requirement of the related striplines, the thickness and permittivity ratio of these two dielectric layers could be selected such that the potential leakage of conductor–backed CPW/slotlines may be controlled as suggested in [15]. It becomes known that the nonleaky coplanar (NLC) waveguide enjoys the benefits of easy fabrication, high tolerance to the change of dimensions, and high mechanical strength. Additional advantageous features are accentuated by the fact that the dispersive microstrips can be made with a flexible choice of line impedance and coupling mechanism between two subsets of structures. This is easily done by a concurrent design approach considering performance requirement of both structures. The coupling and/or interconnection among co–strips and CPW/slotlines can be designed in different manner such as metallic vias [16], solderless electric and/or magnetic interconnects. Self–packaged techniques can also be realized under the proposed scheme. This multilayered technique may offer low–cost, miniaturized, and compact topology with easy alignment and patch fabrication of multilayered modules in the massive production and assembling while compatible with the MMIC processing [2].

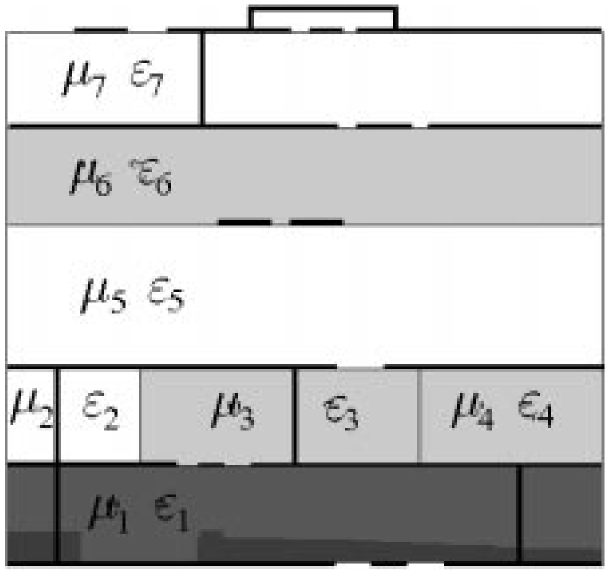
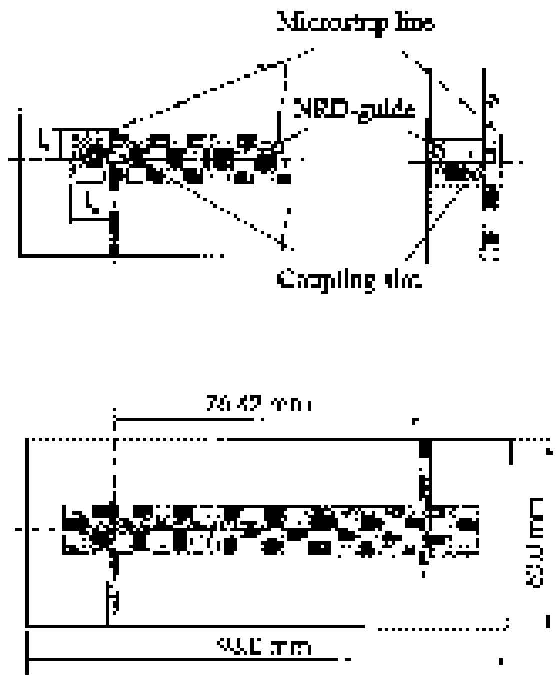


Figure 4. Graphic representation of an alternated 3D multilayered structures consisting of microstrip, slotline, CPW, and stripline.

3. Integration of NRD–guide and planar structure

The NRD–guide technology has been known for its low–cost, low–loss transmission free from radiation loss due to sharp bends and other circuit discontinuities [17]. Therefore, this technique is considered as an attractive alternative for designing millimeter–wave circuits. Its invention has changed the traditional perception related to dielectric waveguide [18]. Following the successful applications of the conventional NRD–guide technology, a new hybrid integration of NRD–guide and planar circuit was proposed [21] and aimed at eliminating the underlying disadvantages of the both building blocks at millimeter–wave frequencies while their technical benefits and design freedom can be maintained.

In contrast to the previously proposed integration of planar circuits with the NRD–guide [9, 18, 19], the new scheme as portrayed in Fig. 5 removes effectively the space constraint of a planar circuit inserted into NRD–guide whose lateral extent is limited by a half of free–space wavelength. The planar structure may be in the form of microstrip line or coplanar waveguide or even slot line. In [20], an integrated transition of microstrip line to NRD–guide is made through a magnetic aperture coupling. The microstrip line is placed at the perpendicular direction to the dielectric strip of the NRD–guide. The microstrip line can be relocated at 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 on the ground plane (the parallel plate).



(a)

(b)

Figure 5. Illustration of a hybrid planar and NRD–guide integration scheme.

Obviously, a number of microstrip lines may be attached on the both sides of the NRD–guide simultaneously. This consideration gives rise to some interesting feature of the proposed hybrid technology such as space saving and interference reduction. Actually, a self–packaged circuit design can be easily achieved. A hybrid planar/NRD–guide filter can be designed at least in the two different ways [21], to name an application example. The input and output can be located either on the common plane or the opposite planes. In this way, it is possible to design two circuit blocks that are likely to have a strong parasitic coupling into two different layers and they can be connected through the aperture–based back–to–back transition. It is obvious that the passive components made of the NRD–guide will present unmatched performance such as high–Q, low–loss transmission, radiationless, and potential cost–effective. The advantages of the planar structures are exploited for the design and realization of two– or three–terminal based active devices [21, 22] such as easy integration and use of M(H)MICs. This new technology presents a high–level integration involving dielectric waveguide and planar circuits that may be in the form of MICs, MHMICs and MMICs. On the other hand, the dielectric waveguide can also be used to design a highly efficient millimeter–wave antenna [27].

The integrated transition (balun) 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 [20,23,24,25,26,27] for the LSM–mode related transitions between the NRD–guide and microstrip line with modeling and experimental results. Very recently, a new LES–mode transition has been also developed for the hybrid application [31], which may be explored to design some components or devices such as mixer that employ the property of mode orthogonality since the LEM– and LSM–modes are orthogonal in space. Obviously, the proposed hybrid technology is potentially low–cost since the basic design of the NRD–guide based components is related to a series of mechanic fabrications and assembling of integrated and discrete devices and components. This issue may be better judged on the basis of an oscillator design at millimeter–wave frequency [32], in which the conventional ceramic–based DR technique may be rather expensive. The conventional technique presents also some challenging in view of circuit design that can be surmounted by the proposed hybrid integration scheme [32].

4. Potential problem and future direction

The above discussed new development suggests that the 3D hybrid design technique present most likely a next generation of the most important microwave and millimeter–wave integrated circuit/system building blocks involving interconnects, packaging, antennas and digital circuits. It is also possible to have a mixed integrated optical and electrical signal design on the same building block such that the optoelectronic ICs is also a part of such a 3D system. Considering the fact that a multilayered 3D planar integrated structure is readily integrated with the NRD–guide circuits, it is anticipated that a generalized hybrid 3D technology of planar/non–planar multilayered circuits can be designed for microwave and millimeter–wave as well as optoelectronic applications. This 3D–module design involves NRD–guide, various planar lines in the form of MMICs and micromachined structures. This is to say that the NRD-guide can be designed and fabricated within the MMIC module. In this case, the NRD–guide should be in the form of a dielectric layer with complete dielectric extent into the bilateral directions and the NRD–guide is a non-dielectric guide surrounded by dielectric materials whose permittivity is smaller than its core part. Of course, the spacing between the two metallic plates should be much smaller than the conventional NRD–guide that is concerned only the free–space wavelength. There are also possibilities to design truly integrated NRD–guide circuits based on the micromachining technique such as Silicon– or Polyimide–based NRD–guide for millimeter–wave and submillimeter–wave applications. Interestingly, the resulting multilayered structure supports simultaneously wave propagations with various modes in different layer having potentially different operating frequencies. In addition, antennas can be realized with the leaky–wave NRD structures that may be integrated into the multilayered topology. The complete transceiver can be designed with maximum compactness and efficiency.

Other interesting aspects of the proposed 3D multilayered hybrid integration may be also related to the use of new materials for the multilayer. The ferroelectric or chiral materials can be easily implemented in the proposed planar and nonplanar structure to achieve on–chip external electronic or magnetic tuning function. This is because the NRD–guide is always sandwiched between two metallic plates, which points to an easy external biasing. In addition, some advanced nonlinear materials can be considered to design active NRD–guide devices without resort to lumped active elements such as diode and transistor. Apparently, these conventional diode or transistor has limited operating frequency as the building block is relied on the lumped–type circuit. In the proposed 3D planar/nonplanar integrated circuits, it is possible to design truly distributed devices using nonlinear transmission line (NLTL) technique such as millimeter–wave or submillimeter–wave amplifier within the nonlinear NRD–guide scheme that is very similar to the optical amplifier design mechanism.

A number of challenging issues is expected that be directly related to the 3D design and fabrication. First of all, the design should be field–theoretically based because the whole structure supports complicated wave propagation and signal routine. Since the 3D system design may deal with planar and nonplanar (NRD–guide) topologies and also digital and analog chips, interconnects and packaging issues are much more involved. Of course, the integration of active devices and passive circuits under a 3D design becomes difficult, and the ground planes and biasing lines should be appropriately arranged. In addition, potential problem of the 3D design may be related to possible radiation loss and mode conversion problems since the transition/balun usually presents an unbalanced geometry from the viewpoint of both nonplanar (NRD–guide) and planar lines. In particular, the unbalanced (or asymmetrical) topology may be a critical factor for designing NRD–guide, for example. In our opinion, the aperture–based coupling will not lead to any visible leakage of power or mode conversion since it will not disturb the electric field profile of the fundamental nonradiative mode (LSM mode). Usually, the NRD–guide presents a high impedance that may cause the serious problem of an impedance matching with the planar circuit if a low dielectric material is used for the NRD–guide. Therefore, a search for better transition/balun should be made to develop successful 3D millimeter–wave circuits and systems [28, 31].

To improve the effective bandwidth performance and coupling efficiency (reduction of insertion loss) as far as the hybrid planar circuit/NRD–guide technology is concerned, alternative aperture geometries and coupling topologies should be studied for multilayer based aperture coupled antenna and circuit applications [29,30], which may be useful in the design of the line–to–line or NRD–to–line transitions. Therefore, a systematic study should be made for transitions/baluns serving to connect NRD–guide with planar lines or two dissimilar structures. The insulated NRD-guide was proposed for the use of high dielectric permittivity materials. Further study on this type of NRD-guide transitions to planar circuits should be considered.

5. Conclusion

This paper reviews the hybrid integration technique of NRD–guide–to–planar circuit and 3D planar circuit–to–planar circuit (MMICs and micromachined ICs) that have been proposed for microwave and especially millimeter–wave applications. It has been demonstrated that the proposed hybrid scheme has a number of attractive features for designing passive components and active devices which can be summarized as low–cost, compactness, flexibility of design and reduction of interference. On the other hand, these various hybrid techniques can be considered as a generalized 3D hybrid multilayered planar and nonplanar integrated structure with multifrequency and multifunction characteristics for designing the next generation high–frequency ICs. Some potential problems and possible solutions have also been presented in the paper. Future research direction on this particular subject is also briefly indicated with a class of new designs. It is believed that this new 3D hybrid technique offers a potentially cost–effective and performance promising solution for widespread applications.

Acknowledgment

The author would like to acknowledge technical contributions from his students and post–doctoral fellows. In addition, The Canadian NSERC has financially supported this research program through a strategic grant. Finally, the author would like to express his gratitude to the Telecommunication Research Center and Department of Electronic Engineering at the City University of Hong Kong for the support during his tenure of a visiting professorship.

REFERENCES

1. Holger H. Meinel: *Commercial applications of millimeterwaves history, present status, and future trends.* IEEE Trans. Microwave Theory Tech., vol. 43, pp. 1639–1653, July 1995.
2. M. Hirano and al.: *Three–dimensional passive circuit technology for ultra–compact MMIC's.* IEEE Trans. Microwave Theory Tech., vol. 43, pp. 2845–2850, Dec. 1995.
3. T.M. Weller, L.P. B. Katehi and G.M. Rebeiz: *High performance microshield line components.* IEEE Trans. Microwave Theory Tech., vol. 43, pp. 534–543, March 1995.
4. C.Y. Chi: *Planar microwave and millimeter–wave components using micromachining technologies.* Ph. D. dissertation, Univ. of Michigan, Ann Arbor, 1995.
5. K. Wu and D. Maurin: *Alternated multilayered CPW/slotline/microstrip hybrid techniques for compact RF and microwave circuits.* (invited paper) PIERS, page 444, Jan. 6–9, 1997, Hong Kong.
6. Wilfried Grabherr, Bernhard Huder, and Wolfgang Menzel: *Microstrip to waveguide Transition compatible with mm–wave integrated circuits.* IEEE Trans. Microwave Theory Tech., vol. 42, pp. 1842–1843, July 1995.
7. F.J. Villegas, D.I. Stones and H.A. Hung: *A novel waveguide–to–microstrip transition for low–cost millimeter–wave and MMIC applications.* 1997 IEEE MTT–S Inter. Microwave Symp., pp. 739–742, Denver, June 1997.
8. S. Kanamaluru, M. 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. AP–44, pp. 964–974, July 1996.
9. T. Yoneyama: *Nonradiative dielectric waveguide.* Inferred and Millimeter wave, Academic Press, Inc. Vol. 11, Ch.2, pp. 61–98, 1984.
10. T. Tokumitsu, M. Aikawa, and K. Kohiyama: *Three–dimensional MMIC technology: a possible solution to masterslice MMICs on GaAs and Si.* IEEE Microwave Guided Wave Lett., vol. 5, pp. 441–413, Nov. 1995.
11. K. Onodera, M. Hirano, M. Tokumitsu, I. Toyoda, K. Nishikawa and T. Tokumitsu: *Folded U–shaped microwire technology for ultra–compact three–dimensional MMIC's.* IEEE Trans. Microwave Theory Tech., vol. 44, pp. 2347–2353, Dec. 1996.
12. I. Toyoda, T. Tokumitsu and M. Aikawa: *Highly integrated three–dimensional MMIC single–chip receiver and transmitter.* IEEE Trans. Microwave Theory Tech., vol. 44, pp. 2340–2346, Dec. 1996.

13. K. Kamogawa, T. Tokumitsu and M. Aikawa: *Multifrequency microstrip antennas using allumina–ceramic/polyimide multilayer dielectric substrate.* IEEE Trans. Microwave Theory Tech., vol. 44, pp. 2431–2437, Dec. 1996.

14. J. Papapolymerou, J.C. Cheng, J. East and L.P.B. Katehi: *A micromachined high–Q X–band resonator.* IEEE Microwave Guided Wave Lett., vol. 6, pp. 168–170, June 1997.

15. Y. Liu and T. Itoh: *Control of leakage in multilayered conductor–backed coplanar structures.* 1994 IEEE MTT–S Int. Microwave Symp. Dig., pp. 141–144.

16. K. Wu and al.: *Microwave integrated switching circuits using a hybrid architecture of microstrip and coplanar waveguide.* Proc. of 1995 Asia–Pacific Microwave Conf., pp. 470–473,

17. T. Yoneyama: *Nonradiative dielectric waveguide for millimeter–wave integrated circuits.* IEEE Trans. Microwave Theory Tech., vol. 29, pp. 1188–1192, Nov. 1981.

18. T. Yoneyama: *Recent development in NRD–guide technology.* Ann. Télécommun., 47, no.11–12, pp.508–514, 1992.

19. F. Furoki and T. Yoneyama: *Nonradiative dielectric waveguide circuit components using beam–lead diodes.* Electronic and Communications in Japan, Part 2, vol. 73, pp.35–40, No.9, 1990.

20. 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.

21. K. Wu, and L. Han: *Hybrid integration technology of planar circuits and NRD–guide for cost–effective microwave and millimeter–wave applications.* IEEE Trans. Microwave Theory Tech., vol. 45, pp. 946–954, June 1997.

22. K. Wu and L. Han: *Integrated planar NRD oscillator suitable for low–cost millimeter–wave applications.* IEEE Microwave and Guided–Wave Letters, Vol. 6, pp. 329–331, Sept. 1996.

23. L. Han, N. Simons, K. Wu, A. Ittipiboon and M. Cuhaci: *Experimental and numerical investigation of a microstrip to NRD transition.* Conf. Proc. of ANTEM'96, pp. 15–18, Aug. 6–9, Montreal.

24. L. Han and K. Wu: *An Integrated Transition of CPW to NRD–guide for use in millimeter–wave circuits.* 1996 Asia–Pacific Microwave Conf. Digest (APMC'96), pp. 1277–1280, Dec. 17–20, India.

25. K. Wu and L. Han: *The hybrid integration technique of planar and NRD–guide circuits for millimeter–wave applications.* invited presentation at 1996 WRI Inter. Symp., on Directions for the Next Generation of MMIC Devices and Systems, Polytechnic University, New York.

26. K. Wu and L. Han: *The hybrid integrated planar/NRD–guide technology: a new concept for low–cost application of microwave and millimeter–wave circuits.* 1996 IEEE MTT–S Inter. Microwave Symp., pp. 91–94, San Francisco, June 1996.

27. H. An, K. Wu and R.G. Bosisio: *Analytical and experimental investigations of aperture–coupled unidirectional dielectric radiator arrays (UDRA).* IEEE Trans. Antennas Propagat., Vol. 44, pp. 1201–1207, Sept. 1996.

28. A. Bacha and K. Wu: *Towards an optimum design of NRD–guide and microstrip line transition for hybrid integration technology.* Submitted for publication in IEEE Trans. Microwave Theory Tech.

29. V. Rathi, G. Kumar and K. P. Ray: *Improved coupling for aperture coupled microstrip antenna.* IEEE Trans. Antennas Propagat., vol. AP–44, pp. 1196–1198, Aug. 1996.

30. C. Chen, M–J. Tsai and N.G. Alexopoulos: *Optimization of aperture transitions for multiport microstrip circuits.* 1996 IEEE MTT–S Inter. Microwave Symp. Digest, pp. 711–714, June 17–21, San Francisco.

31. A. Bacha and K. Wu: *LES–mode balun for hybrid integration of NRD–guide and microstrip line.* IEEE Microwave and Guided–Wave Letters, to appear in the May issue of 1998.

32. S. Qi, K. Wu and Z. Ou: *Hybrid integrated HEMT oscillator with a multiple ring non–radiative dielectric (NRD) resonator feedback circuit.* accepted for IEEE Trans. Microwave Theory Tech.