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Hybrid 3D integrated circuits at millimeter-wave frequencies –advantages and trends

Ch. PERSON*,
E. RIUS*,
J. Ph. COUPEZ*

Abstract

The implementation of passive RF functions is usually done by means of coplanar waveguides at mm-wave frequencies. We propose original solutions for improving their reliability, by integrating the parasitic mode filters as dielectric bridges through a 3D integration approach. Furthermore, original compensating methods are proposed in order to control the cut-off frequencies induced by the bounding networks.

The 3D hybrid approach can also be efficiently used so as to accommodate the association between active, passive and radiating components. The 3D-CPW technology is therefore completed with Thin Film MicroStrip configurations (TFMS), while composite ceramic/foam architectures become thinkable for radiating arrays.

Key words: Microwave integrated circuit, Hybrid integrated circuit, Millimetric wave, Three-dimensional integration, Coplanar technology, Microstrip line, Antenna array, Patch antenna, Dielectric substrate, Multilayered structure.

type microruban sur substrat mince (TFMS), tandis que des architectures composites céramique/mousse deviennent envisageables pour intégrer les antennes en réseau.

Mots clés : Circuit intégré hyperfréquences, Circuit intégré hybride, Onde millimétrique, Intégration tridimensionnelle, Technologie coplanaire, Ligne microruban, Antenne réseau, Antenne plaque, Substrat diélectrique, Structure multicouche.

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- II. Emerging integration techniques for mm-wave applications
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- IV. Hybrid integration: Benefits of a 3D approach
- V. Conclusion

I. INTRODUCTION

Wideband and multimedia services contribute today to the development of millimetre-wave applications regarding required data bit rates and point to multipoint distribution constraints. The maturity of the technology at such frequencies still remains a critical issue for the manufacturers. They need to deliver to private and public users, commercial systems at reduced cost and with multiple possibilities.

In this way, significant efforts are provided to improve and accommodate new integration technologies for both the operators delivering new competitive services with respect to the cable (Local Access Network, Wireless Local Loop,...), and the customers (interactivity, vod,...).

The integration reproducibility and reliability become one of the key parameters, as well as the problem of compatibility between the sub-modules constituting the RF front-ends of such wireless equipments.

In this paper, we focus on original technological solutions which can be proposed in order to meet the previous described requirements.

INTÉGRATION HYBRIDE 3D AUX FRÉQUENCES MILLIMÉTRIQUES : INTÉRÊTS ET TENDANCES

Résumé

Le développement de fonctions passives radiofréquences est généralement effectué par l'intermédiaire de guides coplanaires aux longueurs d'onde millimétriques. Nous proposons des solutions originales pour améliorer leur fiabilité, par l'intégration de filtres de modes parasites sous forme de ponts diélectriques intégrés multicouches. Des méthodes de compensation originales sont proposées afin de maîtriser les fréquences de coupure induites par ces réseaux de ponts diélectriques.

L'approche hybride 3D proposée peut également être mise à profit pour optimiser l'interaction entre composants actifs, passifs et rayonnants. La technologie coplanaire 3D est ainsi complétée par des configurations de

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II. EMERGING INTEGRATION TECHNIQUES FOR MM-WAVE APPLICATIONS

In the past few years, the intensive development of mm-wave applications has significantly contributed to the evolution of integration technologies and techniques.

The waveguide solution is certainly the best approach in terms of electrical performances (losses), but brings also drastic constraints regarding compatibility (in particular with active MMICs), size, and as a consequence cost. For these reasons, the traditional machined copper structures have been replaced by plastic injected or molded waveguides [1]. This is a significant contribution for the reduction of cost and weight, with the condition that specific metallisation procedures are used (loss considerations), but also for design flexibility (complex geometrical shapes available).

For instance, such an approach has been efficiently used for implementing high performance filters, diplexers and antenna arrays [2]. Also, the reliability with active mm-wave components induces the use of restrictive transitions and interconnecting structures for according volume (waveguide) and printed MMIC (Monolithic Microwave Integrated Circuits) technologies. For such reasons, the CPW technology has been considered for a long time as the only solution for developing mm-wave integrated functions, with reasonable tolerances in terms of cost, performances and reliability. Indeed, in comparison with microstrip architectures, the proposed one brings interesting properties, especially about design flexibilities (according to the additional design variables) and losses, the electric and magnetic fields being concentrated at the dielectric-air interface instead of within the dispersive dielectric substrate.

The major drawbacks of this emerging technology lie in the control of the fundamental parasitic dispersive modes rejection by means of filtering air-bridges, as well as microstrip or parallel plate modes potentially generated when a metallic packaging is used.

Such constraints have motivated the numerous efforts of MMIC designers for developing integrated air bridges (for reproducibility and modelisation reasons) [3]. This way, the achievable reduced dimensions (CPW slot widths) are considered for reducing backward radiations in expectation of packaging incidences.

On the other hand, the MMIC technology is really dedicated to component mass-production. The actual trend followed by designers is rather oriented towards hybrid technologies for meeting cost, reconfigurability and other drastic requirements specifically imposed by emerging mm-wave markets. In addition, RF filters and antennas can not reasonably be implemented on GaAs or InP semi-conductor substrates for size and cost motivations, as well as for efficiency reasons.

The achievement of hybrid technology for mm-wave wireless services appears today as a real opportunity, provided that interconnections with active MMICs can be optimised and electrically well controlled. Furthermore, hybrid technologies are based upon various technological configurations depending on the process and materials involved. This allows one to improve the performances of hybrid systems and sub-systems as original and optimal combination of integrated functions can be manufactured along several methods.

Two fundamental questions have to be answered:

- Which processes (materials, procedure, ...) can be used simultaneously, depending on the basic functions to be associated and integrated?
- How these processes can be combined to lead to an universal hybrid integration procedure for mm-wave products?

III. 3D INTEGRATION TECHNIQUES FOR IMPROVING THE UNIPLANAR TECHNOLOGY

Many studies have shown that the coplanar waveguide can be considered as a good alternative to microstrip lines in the millimeter frequency range [4] (high integration level, interconnection facilities, direct ground connections, great flexibility for circuit design). However, there is one major drawback in dealing with coplanar designs: The parasitic and strongly dispersive coupled slotline mode may be excited by non-symmetrical coplanar waveguide-discontinuities, such as bends or T-junctions for example. The suppression of such perturbing modes is achieved by the insertion of bridges over the centre conductor that enforce identical potential values between lateral ground planes.

Generally, bridges in microwave-integrated-circuits (MIC's) are implemented by thin metallic wires ($\phi \approx 17 \mu\text{m}$), which are bonded to the ground planes as shown on figure 1. However, such an operation induces numerous problems in reproducibility and positioning, which deteriorate the circuit performances. Moreover,

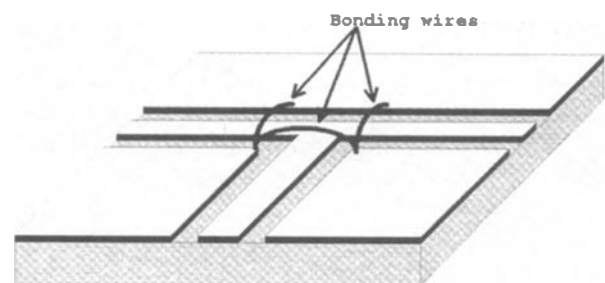


FIG. 1. — Bonding wires on a MIC T-junction.

Filtres de modes sur une jonction en T.

the mechanical resistance of such bridges does not guarantee circuit reliability.

In this paper, we present how these problems can be overcome by using a new multi-layer approach for bridge integration. However, dielectric bridges appear as strong discontinuities on coplanar circuits, and must be compensated. Thus, we propose a way to reduce the parasitic influence of the bridges by locally tuning the dimensions of both the bridges and associated compensating lines.

III.1. Thick-film multilayer technology for dielectric bridges

The basic idea consists in using a protective dielectric layer for interconnecting ground planes by means of a thin conductive printed strip. MMICs solutions have been proposed in the literature, leading to suspended bounding strips as mentioned on figure 2. Unfortunately, this can not be used in MIC technology, because of etching possibilities that are presently available.

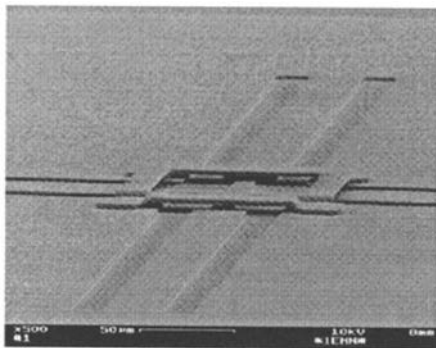


FIG. 2. — MMIC bridges (courtesy of IEMN-Lille [3]).

*Ponts intégrés en technologie MMIC
(contribution IEMN Lille [3]).*

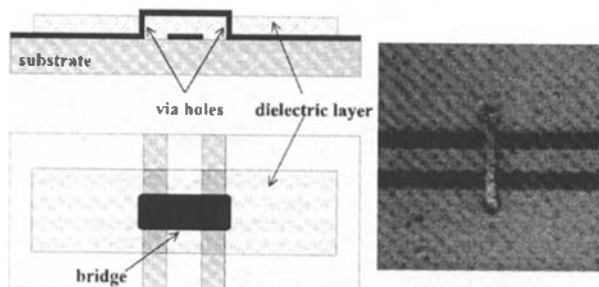


FIG. 3. — Dielectric bridge in a multilayer technology.

Pont diélectrique intégré en technologie multicouche.

To overcome such limitations and insure a better mechanical resistance, well-known multilayer hybrid technologies (MHIC) can be employed for implementing dielectric bridges on MICs. Indeed, in accordance with the significant progress accomplished by dielectric ink manufacturers, it becomes thinkable to use standard process, like the Thick Film technology, for realising integrated mode filtering structures among uniplanar guides. As illustrated in figure 3, dielectric layers can be locally or globally laid down over a first conductive level. Via holes are made in this dielectric layer, to ensure electrical connections between the two lower ground planes and the bridge structure. The second conductive level is directly screen-printed and etched on the upper side of the dielectric layer.

At mm-wave frequencies, photo-printed dielectric materials (HERAEUS ink KQ 110 [5]) are employed to ensure punctual interconnections between the different layers by means of miniature via holes (diameter: 40-50 μm). Notes that laser drilling can also be considered to achieve smaller diameters ($\#10 \mu\text{m}$). This requires a tunable lighthwave equipment (excimer laser) for selecting the materials to be drilled.

The proposed thick film process enables us to obtain robust integrated bridges and eliminate potential problems due to positioning and reproducibility. In addition, this process provides an easy control of bridge dimensions and shape.

III.2. Parasitic influences of the dielectric bridges

Due to the reduced height of the dielectric layers (typically between 10 μm and 20 μm , for the MIC process used), an additional and significant capacitive parasitic coupling effect is introduced between the inner conductor of the coplanar waveguide and the upper short-circuited strip. Obviously, the characteristic impedance and the effective permittivity are significantly modified in the bridge region. In this study, bridges are modelled by equivalent cascaded transmission lines, taking into account the modified electrical parameters of the local multi-layer structure.

Figure 4 shows the influence of the dielectric layer (B) and of the dielectric bridge (C) on the electrical parameters of a 50- Ω coplanar waveguide (A). It should be noted that this type of dielectric bridge presents a sharp discontinuity for the coplanar waveguide. Fortunately, the overall length of a dielectric bridge is usually small, *i.e.* about 50 μm . As a result, the influence of one single bridge on the transmitted RF signal remains negligible below 40 GHz.

However, practical uniplanar designs require a large number of bridges. This results in an accumulation of parasitic effects on the coplanar circuit and, consequently, deteriorates the electrical responses.

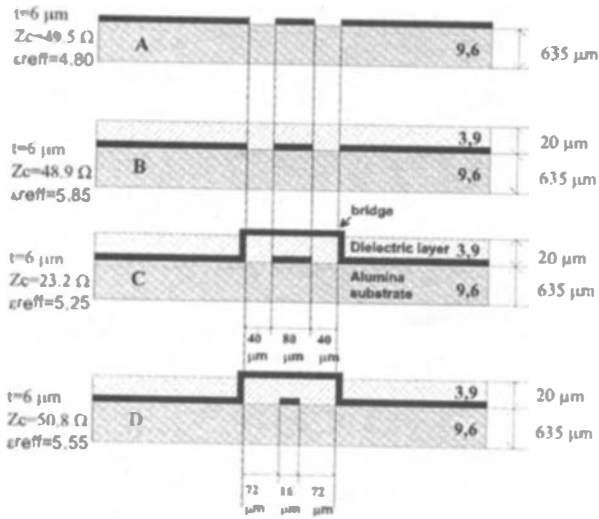


FIG. 4. — Electrical parameters of the integrated bridges.
Paramètres électriques des ponts intégrés.

The figure 5 represents measured return losses of a 50Ω multi-layer coplanar waveguide (strip 80-μm/slots 55-μm) with (curve 1) and without (curve 2) a dielectric bridge. It should be noted that the performances deteriorate rapidly, with a return loss greater than 15 dB at 40.4GHz.

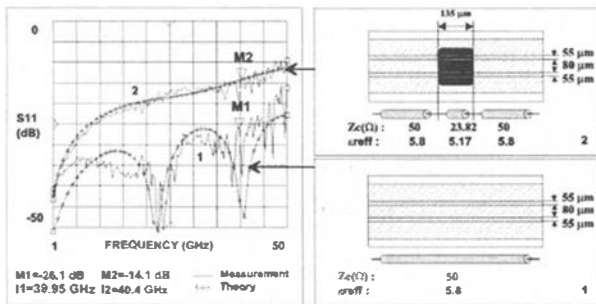


FIG. 5. — Influence of the bridge on a transmission line with/without bridge.

Influence du pont sur une ligne de transmission avec/sans pont.

III.3. Compensating dielectric bridges

Specific procedures must be found for minimising the distortion due to the low characteristic impedance nearby the bridge discontinuity.

The basic idea is to associate high characteristic impedance sections on each side of the bridge, to compensate its low characteristic impedance and recover proper matching conditions [6, 7, 8]. This is achieved by reducing, in an appropriate way, both the width of the inner conductor under the bridge and the distance (D) it extends each side (Fig 6).

The complete structure can now be considered as a low-pass filter (L-C-L equivalent model for A-type compensation) for which the cut-off frequency is related to the parameter D. The dual compensating network can be implemented in a similar way leading to the B-type compensation solution (Fig. 6). The main advantage of this type of structures lies in the reduction of technological constraints: it does not require neither very narrow strips and an accurate positioning of the bridge.

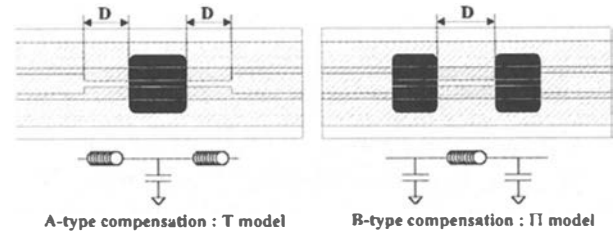


FIG. 6. — Compensated bridge models.

Modèles équivalents des ponts compensés.

III.3.1. Compensated 50-Ω transmission lines: experiment

Various dielectric bridge configurations, with and without compensation networks on 50-Ω coplanar waveguides, can be designed. The length of each dielectric bridge determines the cut-off frequency of the bridge and, therefore, the return loss level within the operating bandwidth.

“On wafer” measurements have been carried out on compensated 50-Ω transmission lines, over the 1 GHz to 50 GHz frequency band. Both types of compensation yield acceptable results with return loss levels better than 24 dB at 40 GHz (see Fig. 7). The compensation technique does not introduce significant additional losses (<0,7 dB up to 40GHz).

III.3.1.1. Bridges efficiency: experimental verification

Circuits including discontinuities, like T- and cross-junctions or bends for instance, generate the parasitic

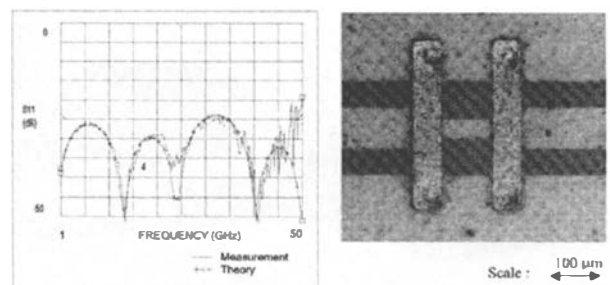


FIG. 7. — B-type compensation.

Compensation de type B.

coupled slotline-mode on a coplanar structure, especially at high frequencies. Therefore, preliminary measurements were first carried out on Te- and cross-junctions to verify the integrated bridges efficiency in suppressing the above unwanted mode. All tested circuits, built on an alumina substrate ($\epsilon_r = 9.6$, thickness = $635 \mu\text{m}$), have $60\text{-}\mu\text{m}$ long bridges.

Despite lumped electrical L-C models are usually used [6, 8], we have implemented distributed models based upon cascaded transmission lines (bend-junction: see Fig. 8). The electrical parameters (Z_c , ϵ_{eff}) per unit length of the lines are calculated with a static finite difference method (2-D analysis).

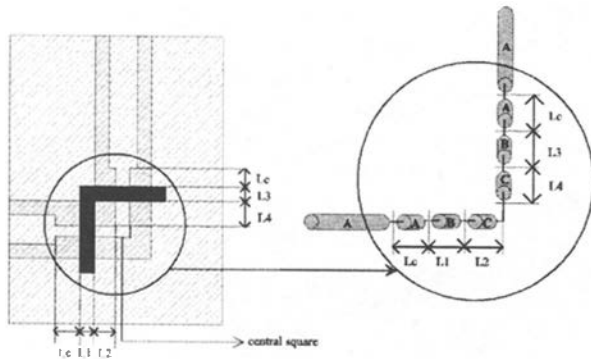


FIG. 8. — Distributed bend model.

Circuit équivalent réparti pour un coude.

Figure 9 describes the behaviour of a cross-junction once all parasitic effects has been properly described and compensated. The measured resonant frequency is equal to 30.4 GHz (30 GHz predicted). According to these results, it thus becomes possible to accurately design a resonator at a fixed frequency. As the compensation tech-

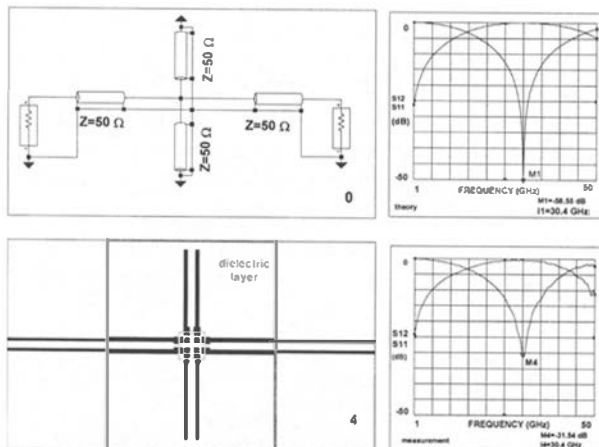


FIG. 9. — Optimised cross-junction: experimental results.

Jonction en croix optimisée: mesures.

nique can be applied to many cases, *e.g.* for different bridge lengths and for different numbers of bridges, various topologies of resonators are available for a given response.

III.3.1.2 Application to wideband millimeter-wave band-pass filter

To validate the above compensated bridges concepts, we designed basic microwave functions such as filters that use integrated bridges. A 5-poles CPW band-pass filter with a 19-dB return loss, 23-GHz operating bandwidth centred at 31 GHz ($\#75\%$ relative bandwidth) was synthesised. First, a standard topology is considered. It consists in symmetrical and asymmetrical short circuited stubs and $\lambda_g/4$ series inverters.

The characteristic impedances and dimensions of each section of the structure are presented in the table of Figure 10. Corresponding experimental performances (with classical bonding) are also shown. It should be noted that the same strip width ($80 \mu\text{m}$) is employed for all resonators. Consequently, only the slot widths are modified to reach the desired characteristic impedances. Differences observed between ideal and experimental values (Fig. 10) are mainly due to the fact that junctions were not taken into account in this design model, as well as the air bridges.

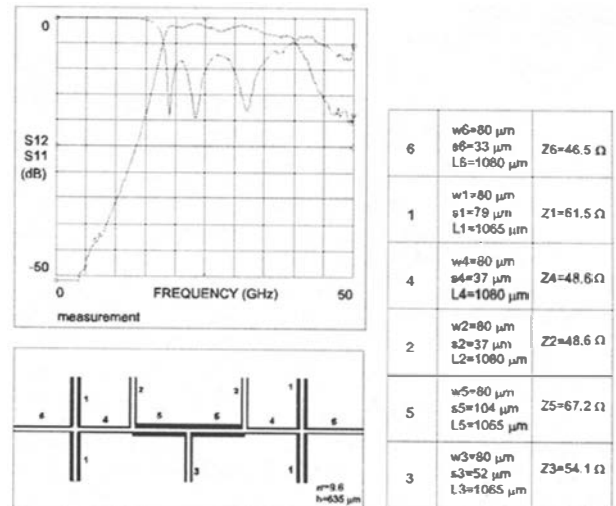


FIG. 10. — Band-pass filter in classical coplanar technology.

Filtre passe-bande en technologie coplanaire standard.

Figure 11 deals with the same filter theoretical characteristics as above, but implemented this time in a multi-layer technology. This allows the implicit integration of compensated dielectric bridges. Equivalent distributed scheme of bridges and junctions are included in the design model. Each discontinuity can now be perfectly controlled and matched.

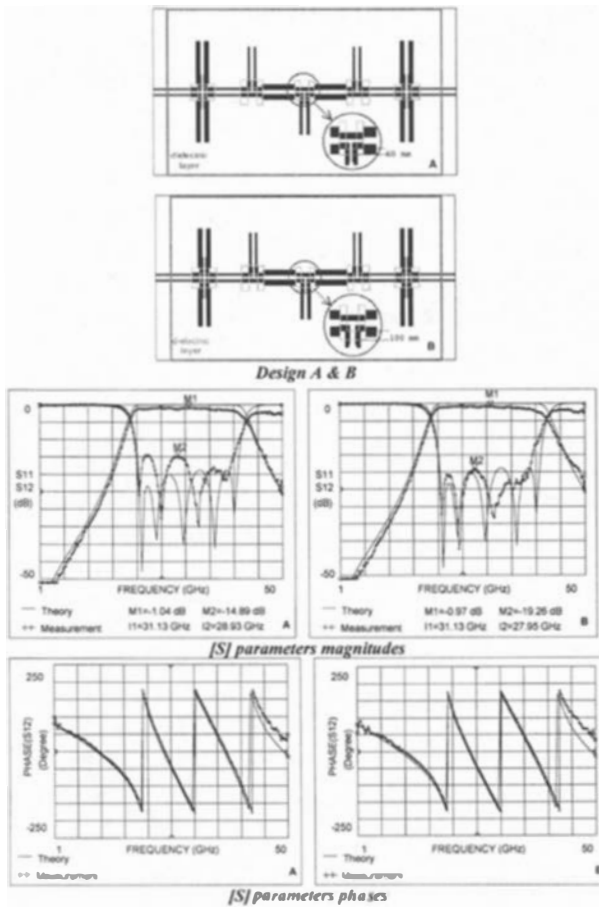


FIG. 11. — Experimental and theoretical results of compensated multilayer coplanar band-pass filters.

Résultats théoriques et expérimentaux pour des filtres passe-bande multicouches compensés.

The first prototype (A) uses 60- μm -long bridges with respect to the central CPW line. The compensation of the prototype (B) was determined in relation with the 100- μm bridge located on the central conductor. Experimental results are in agreement in both magnitude and phase with the desired responses.

Moreover, it should be noted that return losses are about 15 dB in the first case and 19 dB in the second case. Insertion losses are around 1 dB at the central frequency (31 GHz) and the rejection level is correct.

III.4. CPW technology at MM-wave frequencies: Physical & Electrical limitations

Compared to classical uniplanar technology, the main advantage of the multi-layer uniplanar technology is to provide robust and reproducible integrated bridges. Indeed, with this new technology, it becomes possible to

control both the shape and the dimensions of bridges. Thus, it is easier to model their parasitic effects in terms of fundamental propagation mode.

Nevertheless, the coplanar technology can not be universally used, especially for future wireless systems because of their required operating frequencies and bandwidths. For instance, extremely narrow operating bandwidths have to be respected for wireless point to point or point to multi-point mm-wave links. This imposes specific constraints about RF filters for example. One can still consider a CPW implementation by using separating intermediary ground planes. This achieves low coupling levels between adjacent resonant printed structures. Unfortunately, it has some incidence on the overall dimension (additional losses) of such passive functions, and complicates the modelisation process (full-wave model required).

In this way, additional but complementary guiding structures must be developed and considered to implement both efficient radiating elements and loss-less non-disturbing miniature narrow-band functions.

The previous described 3D CPW technology is this time supposed to ensure the interconnections between different sub-modules constituting the RF front-ends. It behaves like a transparent intelligent interconnecting mother-board, including at the same time biasing networks.

The 3D integration process can be employed once again, to provide the integration of loss-less interconnecting or filtering structures by means of Thin Film Microstrip Lines (TFMS), or efficient radiating stacked elements by using ceramic/foam composite substrate. Such technological orientation is also well-suited for improving reliability with active MMICs.

IV. HYBRID INTEGRATION: BENEFITS OF A 3D APPROACH

Considering multi-layer configurations appears today as a good compromise for optimising size, and performances on numerous RF. functions. As shown before, this can be used for example for improving the reliability of the CPW technology. Previous works were also reported at microwave frequencies. They emphasised on the great interest of using overlapped Metal-Dielectric-Metal configurations, in particular with the microstrip approach. Such an orientation brings a complete design flexibility and has been commonly generalized for bypassing intrinsic limitations of basic MIC technologies [9].

At mm-wave frequencies, additional constraints related to the operating wavelength may also encourage designers to employ 3D architectures:

- The dimensions of the structures become small, then requiring the use of thin substrates (for preventing substrate surface modes)
- Mounting and bonding operations involved with hybrid integrations (to connect active components

and passive functions) may introduce non-negligible perturbations. With the generalisation of chip components and Flip-Chip techniques, the mother-board substrate dimensions should absolutely become compatible with regard to MMIC pads and bumps.

Accessing to such low-loss thin substrates has been a major preoccupation in the past few years, with regard to compatibility, measurement, and access conditions.

Unfortunately, thin substrates or standard ceramic substrates are not really appropriate for integrating radiating elements regarding especially radiation efficiency, gain or achievable bandwidth. On the other hand, high coupling levels can be easily achieved through available overlapping possibilities of multileveled architectures. The combination of multi-layer ceramic substrates and low permittivity foam support appears as an optimal composite substrate for such applications. This is discussed in part IV.2.

IV.1. TFMS technology for MM-wave integration: an attractive and complementary transmission line topology

Thin substrates are recommended at high frequencies for microstrip technology to prevent from parasitic substrate surface modes. Furthermore, in an hybrid integration approach, MMIC active components dedicated to mm-wave applications are characterised by reduced dimensions, especially about external connecting pads. Compatible interconnection techniques must be proposed to minimise electrical associated parasitic effects. The thick-film process can be used for developing Thin Film MicroStrip lines (TFMS) [10] and, as a consequence, 50- Ω feeding line widths comparable to MMIC access pad dimensions.

Figure 12 describes the basic corresponding topology based upon a motherboard alumina substrate, with a first

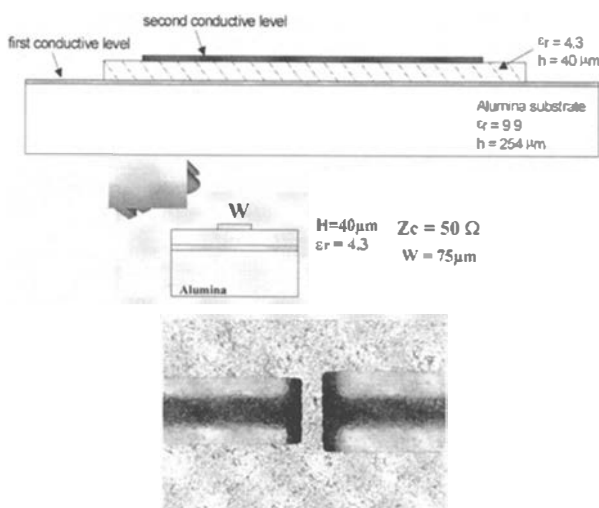


FIG. 12. — Transverse geometry of the TFMS topology.

Description transverse de la configuration TFMS.

conductive layer (assumed as the TFMS ground plane), a thin dielectric sheet (10 to 40 μm) deposited by a screen-printing procedure, and an upper etched layer (microstrip conductor).

In the case of a $\epsilon_r = 4.3/40 \mu\text{m}$ dielectric sheet, a 50- Ω line can be synthesised by means of a very thin strip ($W = 75 \mu\text{m}$) in accordance with the dielectric thickness and, consequently, with common MMIC pad dimensions. In addition, the W/h ratio is compatible with a proper description of the technological structure using standard CAD tools based upon transmission line analysis, despite very high operating frequencies.

Avoiding tedious electromagnetic simulations constitutes a significant advantage. Note that this is not the case when dealing with CPW complex architectures or oversized microstrip ones (with respect to wavelengths).

IV.1.1. Accessing to TFMS structures [11]

The reduced dimensions offered by the TFMS technology are well-suited for designing efficient RF-circuits at mm-wavelengths. However, accessing to such technological structures can bring some problems in terms of dimension compatibility with standard feeding technologies (CPW and microstrip), electrical behaviour (parasitic effects, bandwidth & frequency limitations) and mechanical tolerances.

Thus, we have developed high performances CPW to TFMS transitions, then keeping in mind the advantage of the CPW motherboard concept in the millimeter-wave range. Such a transition is based upon a $\lambda/4$ overlapped coupled lines separated by a thin dielectric sheet which constitutes simultaneously the TFMS substrate. Note that the TFMS ground plane is directly connected to the CPW ground planes and may also be considered as a potential CPW parasitic mode filtering structure (Fig. 13).

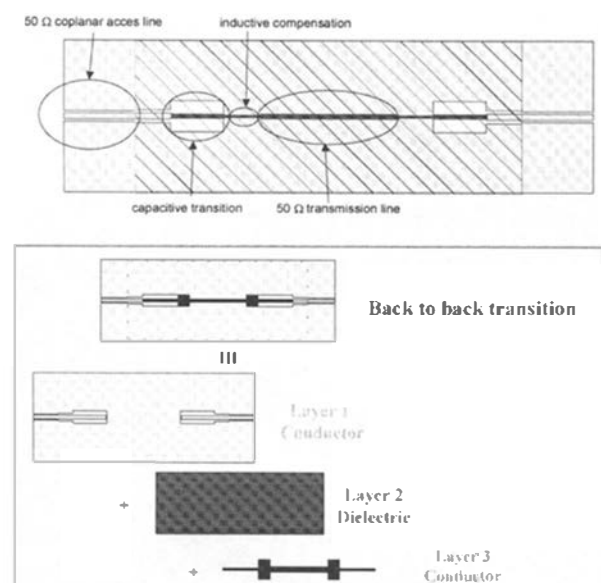


FIG. 13. — Design of a Back to Back CPW to TFMS transition.

Transitions tête-bêche CPW – TFMS: masques.

An optimisation procedure was applied to control the lower and upper cut-off frequencies of this series capacitive coupling structure. Additional inductive and capacitive sections were cascaded each apart from the MIM (Metal-Insulating-Metal) capacitance to lead to a higher order highpass filter.

Quite a wide operating bandwidth can be achieved, as mentioned on figure 14 where experimental results are reported for a 40% relative bandwidth transition (for a -17 dB return loss) centred at 41 GHz. Wider bandwidths can be considered, using the numerous tuning variables, and taking advantage of the wide range of coupling achievable with the 3D approach.

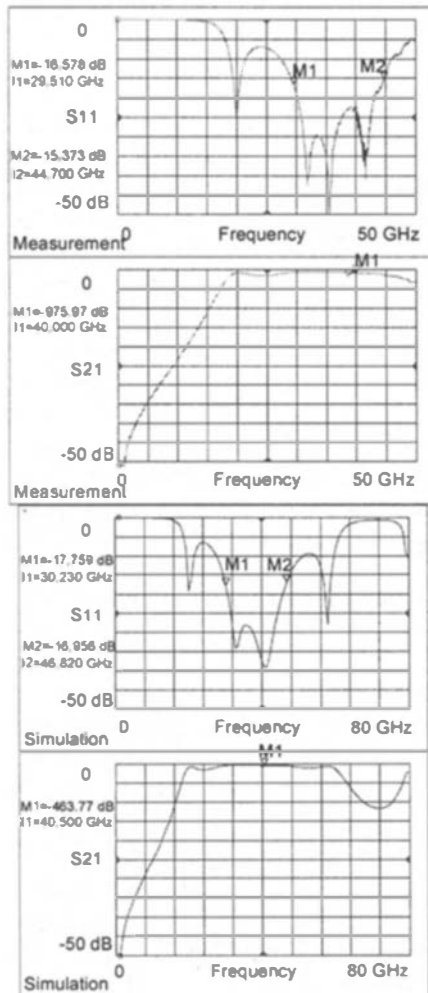


FIG. 14. — Back to back CPW to TFMS transitions: experiment.
Transitions tête-bêche CPW – TFMS: mesures.

Insertion losses of about 0.8-dB only have been registered inside the 15-dB return loss bandwidth for a 1 mm long structure. Such transitions appear really as a convenient solution for improving interconnections between active and passive modules in future millimeter-wave hybrid front-ends.

IV.1.2. TFMS approach for designing efficient passive functions

With the TFMS technology, the strip width becomes fairly small for a wide set of characteristic impedance values. Thus, it becomes therefore negligible with respect to wavelengths in the 30-100 GHz range. In this case, TEM approximations can be considered, and the design of passive function like filters and couplers can be directly implemented using traditional topologies and synthesis methods (parallel coupled lines filters, $\lambda/4$ resonators, etc..). Furthermore, since the substrate thickness is kept small, quite low coupling levels are achieved with standard $\lambda/4$ coupled resonators, even when the smallest etchable spacing is reached (the odd and even mode impedances of the coupled lines are quite similar ($Z_{oo} \approx Z_{oe}$) because of the ground plane proximity).

This is especially attractive for synthesising very narrow-band band-pass filters at mm-wave frequencies. The figure 15 describes a TFMS parallel coupled lines filter designed at 41 GHz, and compared with its corresponding microstrip version on 254- μm alumina substrate.

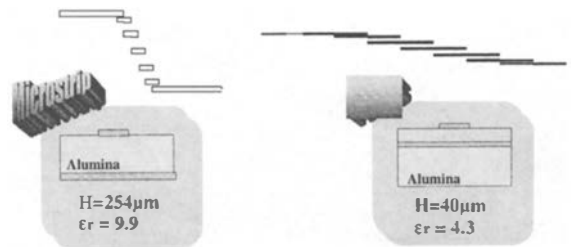


FIG. 15. — TFMS / microstrip layouts of a narrow-band filter.
Filtres faible bande TFMS / microruban: masques.

Note that the L/W and L/S ratios (W, L: Width, Length of the resonators, S: Spacing between adjacent resonators) for each resonator allows a transmission-line description with the TFMS solution.

Figure 16 gives some experimental results obtained with the TFMS filter, including CPW to TFMS transitions for probe testing facilities. No tuning operation is required after manufacturing despite the severe requirements. Some fair agreement is obtained between simulation and measurement given the fact that the transmission losses are not accounted for the model.

Some specific effort must be provided by both manufacturers and designers for decreasing conductive losses with TFMS topologies with the reduced width and thickness of the conductors. Another solution, proposed in

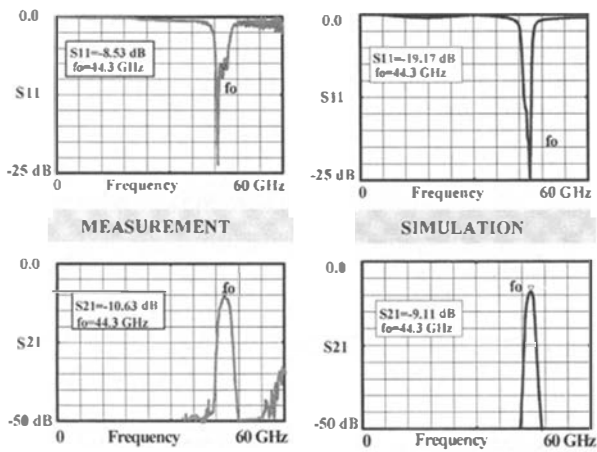


FIG. 16. — TFMS bandpass filter: simulation & measurement.

Filtre passe-bande TFMS : simulations & mesures.

[11] consists in artificially lowering the filter order by using an adequate and original synthesis technique. The CPW to TFMS transition previously described can be considered as an overcoupled resonator (overlapped structure). It can be introduced within the filter which contributes to reduce its size, losses and technological sensitivity.

IV.1.3. TFMS access for improving compatibility with MMIC's

The achievement of commercial mm-wave MMIC's and chip is a key factor for the emergence of hybrid technologies in future applications. The critical dimensions of these new products (typically $200 \times 300 \mu\text{m}$ – thickness $120 \mu\text{m}$) become also critical in an electrical point of view.

The connecting bounding wires usually induce important parasitic effects depending on their length, diameter and contact quality with pads when using microstrip or CPW technologies. Compatible dimensions between the feeding line network and the MMIC pads are not really respected, as well as the common metallic support manufactured for compensating thickness discontinuities.

The TFMS configuration is undoubtedly an attractive solution for accessing to MMICs and chips with lowest perturbation phenomena:

- Dimensions are quite similar between active and passive feeding ports.
- Bounding operations can be made less perturbing by minimizing the number of wires and their length.

Since the MMIC is usually mounted on a ground plane, the thin dielectric sheet can be etched, thus ensuring the perfect control of the chip location when reported on the motherboard alumina substrate. In addition, the ground plane continuity is readily obtained, and no additional bounding wires are required for interconnecting MMIC and CPW or microstrip ground planes (see Fig. 17).

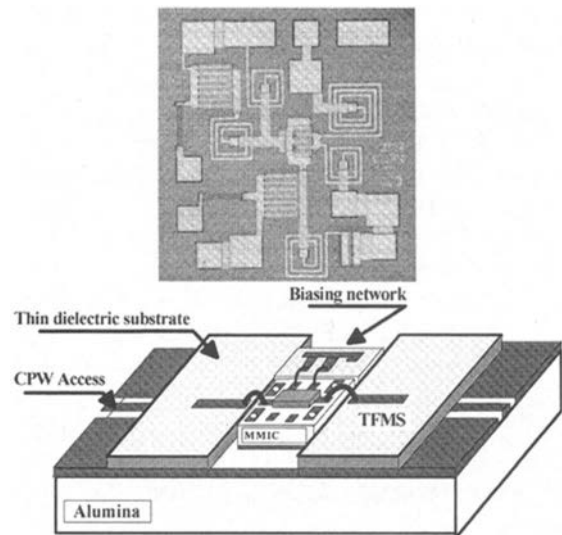


FIG. 17. — Interconnection between MMIC & TFMS technology.

Interconnexion entre les technologies MMIC & TFMS.

IV.1.4. TFMS process attending for mm-wave Flip-Chip components

Finally, Metal-Dielectric-Metal implementation (i.e. TFMS structures) will be found in number of applications that involve future mm-wave Flip-chip components. Photo-imageable dielectric materials are of great interest to realise discrete connections between lower shielded printed structures and upper surface-mounted Flip-Chip components.

Figure 18 depicts a beam-lead schottky diode mounted across a $30 \mu\text{m}$ width slotline, with a separating

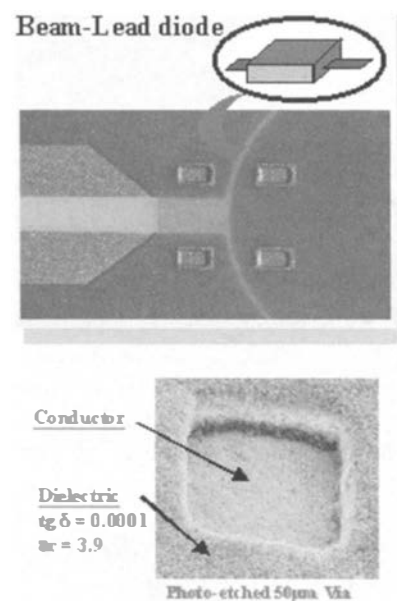


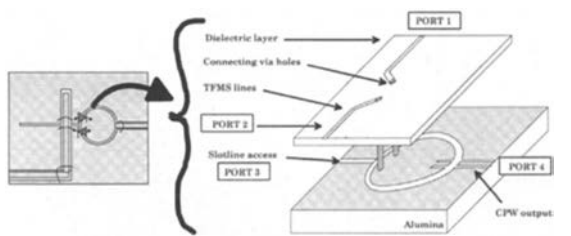
FIG. 18. — Beam-lead Schottky diode across a slotline ring.

Diode de Schottky à conducteurs poutres montée sur anneau à fente.

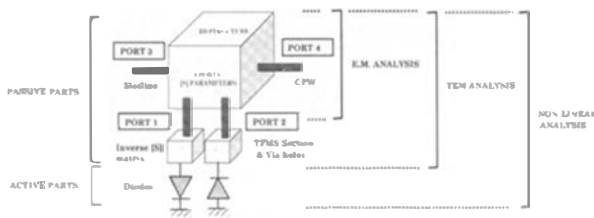
20 μm dielectric layer. The interconnection between the diode pins and the slotline arms is performed through 40- μm via holes.

Numerous advantages appear:

- Using 3D technological process, the passive circuit is completely shielded and protected, thus simplifying mounting
- Such an implementation also contributes to simplify the structure analysis. Indeed, the input impedance can be extracted at the diode connecting ports, using either Agilent-MDS™ multilayer library or 2.5D Agilent-Momentum™ simulator. Consequently, the non-linear modelisation can be done on MDS® once the complete passive structure is modeled as a multiport network. This is illustrated in figure 19 for a balanced mixer based upon an annular slotline structure [12] (Fig. 18).



a - Decomposition of the structure for a local 2D analysis



b - Nonlinear analysis with pre-defined multiport modules

FIG. 19. — Non linear analysis of a 3D CPW mixer: Procedure.
Analyse non-linéaire d'un mélangeur coplanaire 3D : Démarche.

IV.2. Mixing technologies for efficiency and miniaturization

Cost reduction and miniaturization efforts will be achieved in the future if global synthesis and integration techniques are considered. Hence, the radiating network should be located as close as possible to the RF-front-end modules. In addition, this will also result in improving the C/N ratio as well as the reconfigurability of such a module.

With the selected hybrid integration approach, active and passive functions are integrated on alumina motherboard substrate, i.e. high permittivity substrate, for size and sub-modules compatibility requirements. On the other hand, radiating elements must be integrated on low

permittivity thick substrates for radiation efficiency and electrical performances (e.g. bandwidth,...). The hybrid process should accommodate the above requirements which enforce opposite trends in terms of permittivity values.

Once again, the flexibility brought by the 3D concept leads to new prospects for mm-wave applications:

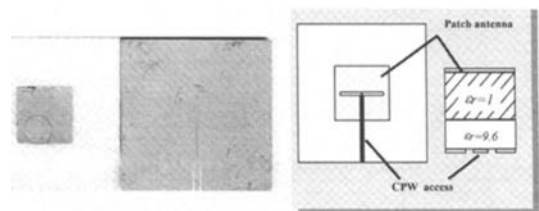
- Constructing composite Ceramic/Foam substrates by combining press-moulding and screen-printing process on alumina motherboard substrate.
- Translating and matching the well-known Membrane process to standard 3D hybrid techniques.

IV.2.1. Composite Ceramic/Foam substrate for global optimisation procedure [13]

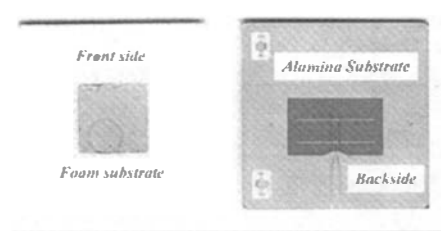
Works on mm-wave antennas are focused today on the used of new well-suited materials, based upon foam ($\epsilon_r = 1.07$) or honey-cell structures which offer excellent performances up to 60 GHz. The metalisation and etching process remain critical procedures. However, few solutions have been recently proposed through press-moulding or chemical deposition techniques.

Printed patch arrays have been implemented on such a support, with specific efforts concerning the miniaturization of the basic radiating elements (better control of the antenna array response), by dielectric insert technique. Difficulties arise when considering the microstrip array feeding network, because of the (ϵ_r, h) values of the substrate: (wide strips \Rightarrow parasitic coupling \Rightarrow side lobes \nearrow , cross-polarisation \nearrow).

Therefore, stacked structures and aperture coupled antenna arrays are used rather than planar configurations, emphasising once again on the benefit of 3D approaches. The figure 20-a describes a microstrip patch antenna



a - Patch antenna with a CPW feeder on a composite foam/ceramic substrate



b - Front side and backside views of an integrated Antenna/filter module

FIG. 20. — Patch antenna on a composite substrate.

Antenne plaques sur un substrat composite.

made on foam substrate fed by a non-resonant slotline located in the ground plane. This slot is excited through a CPW structure made on alumina substrate to obtain efficient coupling.

At mm-wave frequencies, the 3D passive and active functions described before can be directly combined with such antenna arrays on foam material, through the common ceramic mother-board substrate and an intermediate slotline feeding network. Such technique has been validated up to 20 GHz only (see fig. 20-b [14]), but the concept can be easily extended to mm-waves. This original association is obviously a good compromise for combining efficiency and miniaturization criteria in a global integration approach. Notes that specific synthesis techniques have been proposed in order to introduce technological constraints during the design task (global synthesis). This leads to increase the bandwidth of the radiating patch.

IV.2.2. Membrane technology as an alternative solution

The other opportunity, initially proposed by Rebeiz [15], and considered by numerous authors consists in developing membrane antennas. The thin film membrane having a permittivity close to the one of the air, radiation efficiency is increased. In addition, optimal coupling between guided and radiating modes is obtained, which yields wideband high efficiency antenna arrays.

Interconnecting such a technology with standard ones has been a great challenge during the last few years. Various possibilities are now considered [17], by using electromagnetic coupling (comparable to the method mentioned above) or suited mounting techniques. A 4*4 aperture fed membrane antenna array designed at 40 GHz is proposed on figure 21. Each basic radiating patch is designed on a membrane section (for radiating efficiency), while the microstrip feeding network is implemented on a backside substrate for which the ground plane acts as a shielding plane. The excitation of the different elements is therefore made easier through the slot apertures, while parasitic coupling are properly rejected, each antenna being located on an electromagnetic shielded cavity.

Ultra-low cost membrane structures on copper support, processed as Flip-Chip components, and reported

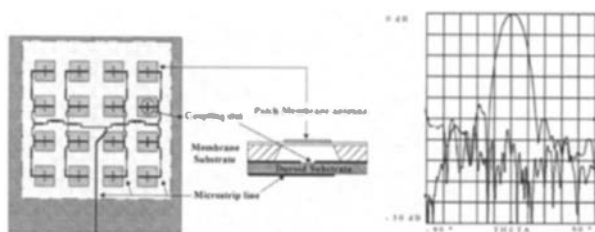


FIG. 21. — Aperture fed membrane antenna array at 40 GHz.

Antenne en réseau à technologie de membranes avec alimentation par fentes à 40 GHz.

on an alumina motherboard substrate were reported in a second time [18]. This is illustrated on figure 22 in the case of a membrane 50-Ω line mounted on an alumina motherboard substrate with CPW access, through miniature bumps (50 μm diameter).

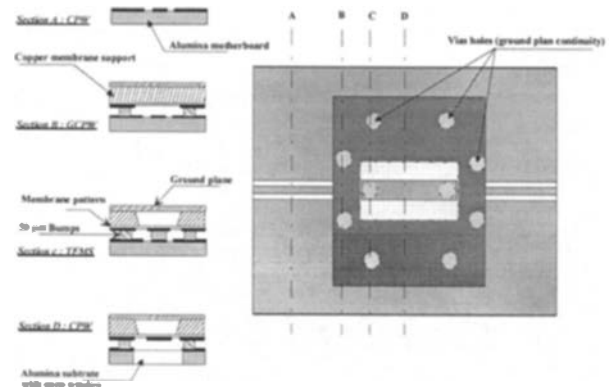


FIG. 22. — Membrane Microstrip line mounted on an alumina motherboard.

Ligne microruban sur membrane montée sur une carte mère en alumine.

This way, one can easily combine 3D functions which are integrated on alumina substrate with membrane modules. These are used for critical sections like antennas or narrow-band filters for which the membrane characteristics should be efficiently selected (losses, radiation efficiency,...).

V. CONCLUSION

The main objective of this paper was to demonstrate that hybrid integration techniques appear really today as attractive solutions for developing low-cost high efficiency mm-wave modules and sub-systems, especially when 3D integration techniques are considered.

On one hand, the reliability of the CPW technology, which can be assumed as the reference technology at such frequencies, can be really improved by implementing integrated dielectric bridges for parasitic modes suppression. Original compensation techniques can be used for controlling the corresponding operating bandwidth.

On the other hand, the uniplanar approach can not be considered as an universal response for integrating any mm-wave functions, with any requirements. Using the hybrid orientation, interconnections between basic functions or elements remain sensitive operations, as well as the development of high performances passive devices (narrow-band filters, antennas network,...). The flexibi-

lity of the 3D integration techniques was therefore investigated, by using various available technological architectures, leading to original structures with improved performances with respect to standard approaches.

Some efforts remain to be done concerning the mounting techniques, especially the flip-chip ones. However, the actual evolution of both the chemical industry (for delivering high performance dielectric or conductive inks) and the electromagnetic simulators should help designers to find optimal integrated hybrid 3D modules. These will remain competitive with regard to MMIC approaches up to 80 GHz [19].

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