The Substrate Integrated Circuits - A New Concept for High-Frequency Electronics and Optoelectronics

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Abstract — **A new generation of high-frequency integrated circuits is presented, which is called substrate integrated circuits (SICs). Current state-of-the-art of circuit design and implementation platforms based on this new concept are reviewed and discussed in detail. Different possibilities and numerous advantages of the SICs are shown for microwave, millimeter-wave and optoelectronics applications. Practical examples are illustrated with theoretical and experimental results for substrate integrated waveguide (SIW), substrate integrated slab waveguide (SISW) and substrate integrated non-radiating dielectric (SINRD) guide circuits. Future research and development trends are also discussed with reference to low-cost innovative design of millimeter-wave and optoelectronic integrated circuits.**

I. Introduction

Low-cost, mass-producible, high-performance and high-yield microwave and millimeter-wave technologies are critical for developing successful commercial RF broadband systems. At millimeter-wave frequencies, in particular, circuit-building blocks including antenna elements are closely related to each other via electromagnetic couplings and interconnect. In this case, the circuit design should be made with a global consideration. The classical waveguide technology is still the mainstream for designing high-performance millimeter-wave systems. However, this matured scheme is not suitable for low-cost mass-production. Tedious and expensive post-fabrication tuning and assembling become a real problem for manufacturers. In addition, the waveguide technique cannot be used to reduce the weight and volume.

On the other hand, challenging problems are often encountered in the design of low-loss ICs, e.g., high-Q bandpass filter and diplexers, to which the planar technique is fundamentally limited in performance. As such, non-planar structures such as the classical metallic waveguide are usually needed, thus hybrid schemes of planar and non-planar structures become attractive. In fact, an easy-to-handle low-cost hybrid design strategy is of critical importance for the development of high-volume millimeter-wave ICs and systems.

A number of design techniques of planar circuits integrated with rectangular waveguide have been reported that may not be so attractive for widespread applications. This is because the designs proposed to date present themselves a real challenge for mass-production with respect to millimeter-wave integration and packaging. In addition, it is difficult and even impossible for achieving a wideband impedance matching between low-impedance active elements (IMPATT diodes, for example) and high-impedance waveguide circuits.

Dielectric waveguide has received little attention for microwave and millimeter-wave circuit designs even though it has been studied since many years. This is because it has two fundamental problems, namely, radiation loss due to discontinuity, and difficult modal transition to planar circuits. The non-radiating dielectric (NRD) waveguide [1] was proposed to resolve most of the drawbacks of dielectric waveguide in connection with the radiation loss. To solve the problem of hybrid planar and non-planar integrations, we have proposed and developed various hybrid design platforms that effectively combine the planar circuits and the non-radiating dielectric (NRD) waveguide [2-3].

Subsequently, we have developed the concept of a new generation of high-frequency integrated circuits called “substrate integrated circuits – SICs”. This new concept has unified the hybrid and monolithic integrations of various planar and non-planar circuits that are made in single substrate and/or multilayer platforms. In this paper, we will demonstrate that the proposed substrate integrated circuits (SICs) [4-5] architecture can serve as the design base for a broad range of hybrid planar/non-planar circuits for millimeter-wave applications. As a matter of fact, the SIC technology can greatly facilitate interconnects and integrations between planar and non-planar circuits, which can be made within a patch fabrication process. At the same time, this scheme can be used to design low-cost high-performance (high-Q) passive circuits such as resonators [6], filters [7], couplers [8], power dividers [9], circulators and antennas [10].

With reference to the planar circuits made of conventional planar transmission lines that may be viewed as “surface-field circuits”, the substrate integrated circuits involve both planar and non-planar structures that are realized and integrated on the same substrate with or without multilayered or laminated geometry. The non-planar waveguides in this case are synthesized in planar form, and they may be considered as “volume-field circuits” in contrast with the above-mentioned surface-field circuits. The SIC concept can be used to synthesize almost all kinds of dielectric-based (or filled) waveguide by simply using air-holes (or other material-filled holes in a general sense) and metallized-holes.

Furthermore, most of these synthesized waveguides are interconnected to planar circuits with simple transitions that are also fabricated on the same dielectric substrate. For the

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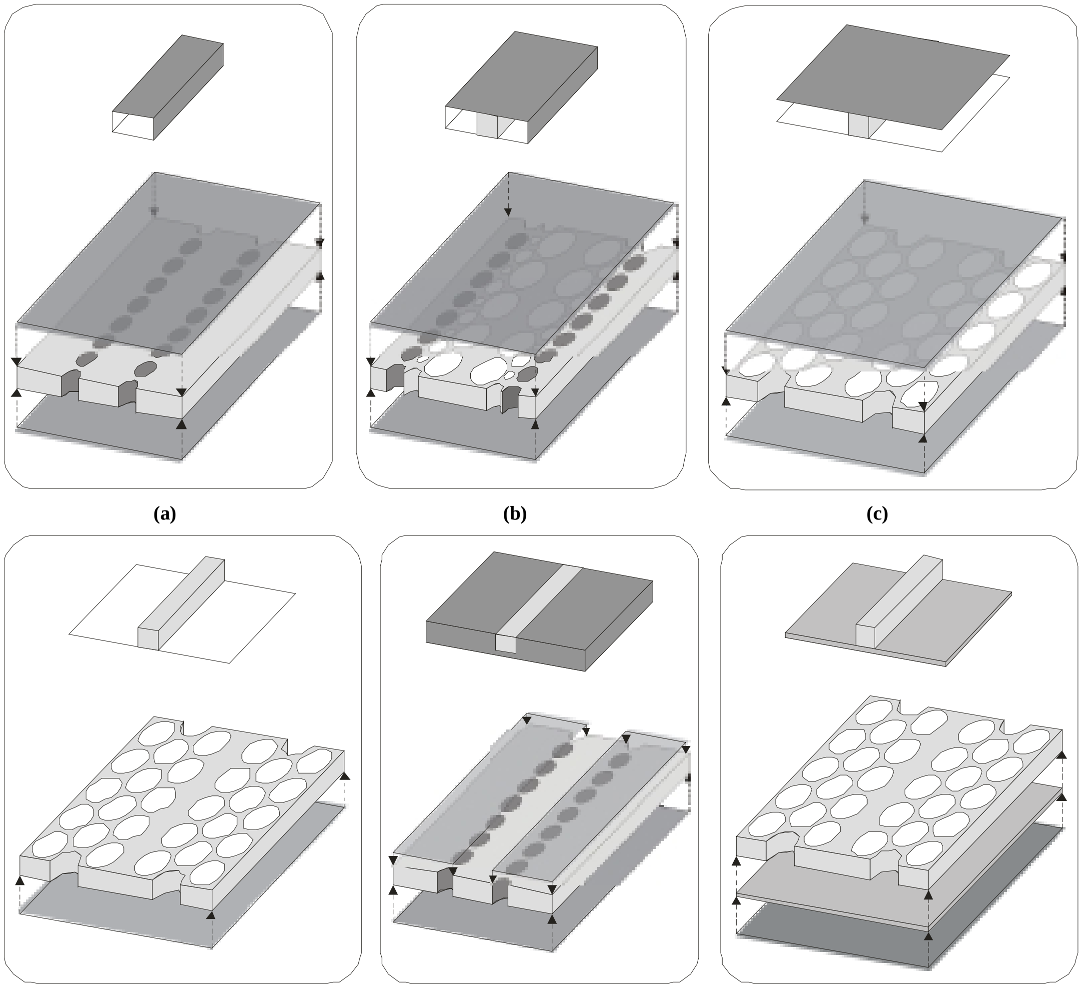


(a) (b) (c)

(d) (e) (f)

Fig. 1 – Topologies of different non-planar SIC structures: (a) Substrate Integrated Waveguide (SIW), (b) Substrate Integrated SlabWaveguide (SISW), (c) Substrate Integrated Non-Radiating Dielectric (SINRD) guide, (d) Substrate Integrated Image Dielectric Guide (SIIDG), (e) Substrate Integrated Inset Dielectric Guide (SIINDG), and (f) Substrate Integrated Insular Guide (SIIG). Note that white circle stands for air hole and dark circle for metallized via. Dielectric material is coloured as light grey.

others, the planar circuits are laminated on the SICs substrate with resorting to fabrication processes such as LTCC.

Four different types of SICs have been demonstrated with a numner of practical examples even though more synthetic non-planar waveguides in planar form can be proposed as shown in Fig. 1. The developed four SIC platforms are respectively called the substrate integrated waveguide (SIW) [11], the substrate integrated slab waveguide (SISW) [12], the substrate integrated NRD (SINRD) guide [5,13-16,26], and the substrate integrated image (or inset) dielectric guide (SIIDG) [10]. Among them, the SIW technology is the most popular and also the most developed platform as it is quite easy to “transplant” the existing and matured modeling and design techniques of the rectangular waveguide components into the SIW that is simply a synthesized rectangular waveguide.

The SIC technology is still in its infancy and its potential needs to be explored and demonstrated even though there are many practical SIC examples that were implemented. Since this technology is compatible with many fabrication processes such as the thin film, HTCC, LTCC and possibly microwave monolithic integrated circuit (MMIC) [15-16], we can expect strong and growing interests in it for many high-frequency applications. In addition, emerging technologies will push forward the development of SICs at an unprecedented pace, which include nano-technologies, new low-loss/smart materials, integrated radio-over-fiber base-station concepts, photonic integrated circuits, millimeter-wave system-on-chip, and many others.

In this paper, we will first present the SIC concept and illustrate possible topologies of different synthetic waveguides. Then, the state-of-the-art of research and development will be overviewed and discussed on the four SIC technologies that are showcased in this paper: SIW, SISW, SINRD and SIIDG. Finally, future trends and interesting aspects will be noted.

II. Substrate Integrated Circuits Concept

The fundamental of the SICs concept is to synthesize non-planar structure with a dielectric substrate and make it in planar form, which is completely compatible with other planar structures. This can usually be achieved by creating artificial waveguiding channels. In this case, alternated dielectric constant profiles of substrate using air holes or composite dielectric media and/or synthesized metallic walls using metallized vias are generally deployed. The resulting structure on the substrate will be a planar waveguide, which has much better loss characteristics than planar counterparts, allowing for the design of millimeter wave high-Q filters, diplexers, resonators and other circuits using a low-cost fabrication technique. Furthermore, the synthesis of a non-planar waveguide in substrate permits the realization of efficient wideband transitions or baluns between the synthesized non-planar waveguide and planar circuits such as microstrip and coplanar waveguide (CPW) integrated circuits. With these baluns and/or transitions, the complexity and cost of interconnection between non-planar high-Q circuits and planar circuits are reduced to a minimum. Thus, a complete millimeter wave front-end circuit for radio and radar applications could be designed and built on one dielectric substrate with only simple fabrication process. This paves the way for developing high-frequency (millimeter-wave) system-on-chip concept if non-linear circuits are also integrated into the same substrate. This can surely reduce considerably packaging, interconnect and assembly problems that are found in current millimeter wave radio equipments.

Note that the periodic air hole patterns used in the realization of some of the SICs should not generate electromagnetic bandgap phenomena (EBG). The use of the air holes is solely for reducing the dielectric constant value of substrate in the specific regions. The EBG phenomena would disrupt the normal propagation of the waveguide modes, which can be avoided by adequate design of the structure.

The SIC concept can be applied to many types of non-planar waveguide that are then made in planar form. Fig. 1 illustrates the application of the above-mentioned SIC synthesis approach to a number of classical waveguides. This figure gives a set of original and corresponding synthetic structures. They include the rectangular waveguide, slab waveguide, NRD guide, image guide and inset guide that can all be synthesized within a dielectric substrate by using air hole and/or metallized via patterns.

Transitions between the SIW and planar circuits such as microstrip, CPW or slotline circuits can be built on the same substrate, as we have discussed. In this case, microstrip and CPW transitions are used to excite the TE_{10} waveguide mode for the SIW while the slotline transition may easily excite the TE_{01} waveguide mode. The same scenarios can also be applied to the SISW and SIINDG. For the SINRD guide, SIIDG and SIIG, the planar circuits are usually fabricated with a conventional technique on a separate substrate that can then be laminated onto the SICs. The reason is that the air holes, which may deal with removing much of the metal part on the SIC substrate, would usually prohibit the fabrication of planar circuits on the same substrate unless some sophisticated process is involved. In this case, transitions from the SIW to SINRD or SIIDG, which have already been developed for the conventional structures [17-18], can be deployed in a straightforward manner. Typically, slotline to SIW transitions would be used to complete such interconnect with planar circuits. This alternative approach is interesting because it could provide wideband transitions. Another potentialadvantage of the SIC technology is that the planar circuits could easily be combined with many types of SICs on the same dielectric substrate so to achieve high efficiency and high-density millimeter wave integrated circuits in which antenna, circulator, filters, attenuators, amplifiers and mixer and many other circuits are all integrated. This is in particular interesting when a thick substrate with CPW circuits designed on the both sides of the substrate and they may be not related to each other on the basis of some careful design. On the other hand, different synthetic waveguides may exhibit quasi-orthogonal field polarizations in space that can effectively be explore to design special circuits such as magic-T and many other circuits. One of such examples is the use of SIW and SINRD guide within the same substrate in which the TE10 waveguide mode and LSM modes are orthogonal I space. Indeed, various features of the SICs can be used to design many innovative circuits and components.

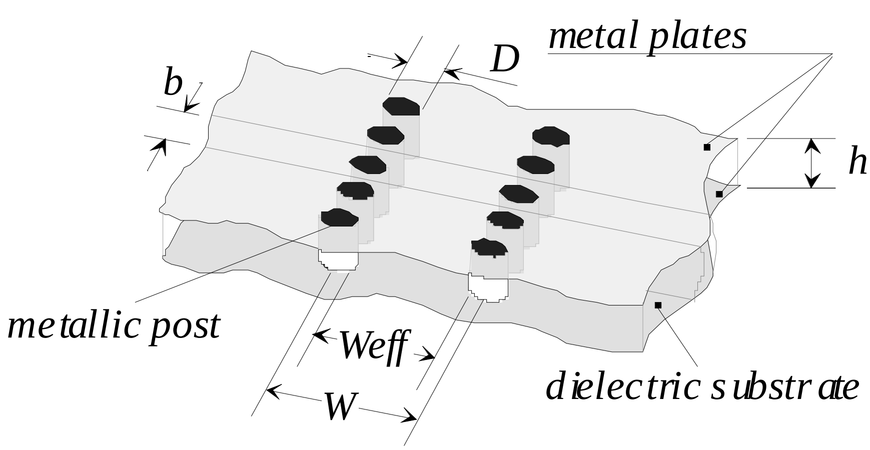


Fig. 2 – Topology of an SIW guide realized on a dielectric substrate with its physical dimensions.

Finally, the SIC concept is compatible with many existing fabrication processes including the microwave integrated circuit (MIC) fabrication technique, the thin-film ceramic process, the HTCC and LTCC technologies and possibly the microwave monolithic integrated circuit process (MMIC). Generally, the critical aspect of fabricating SIC circuits is the positioning of the holes or vias along the substrate that should be controlled adequately. In the following sections, we will discuss the current state-of-the-art of the SIC technologies in connection with the above-quoted topologies.

III. SUBSTRATE INTEGRATED WAVEGUIDE (SIW)

It is known that the proposed integration schemes of the conventional rectangular waveguide with planar structures are bulky and usually require a precision machining process, which is difficult to achieve at millimeter-wave frequencies for mass production. A straightforward solution is to integrate the rectangular waveguide into microstrip circuit substrate as we have briefly discussed in the above section. This will surely reduce the Q-factor of waveguide compared with the hollow rectangular waveguide because of the dielectric filling and volume reduction. The whole circuit including planar circuitry, transitions and waveguides can be, however, constructed using standard PCB or other planar processing techniques. In addition, the transmission loss of the on-substrate transitions may be much lower than that of the transitions or coupling sections made between the conventional waveguide and planar circuits.

A. SIW DESIGN RULE

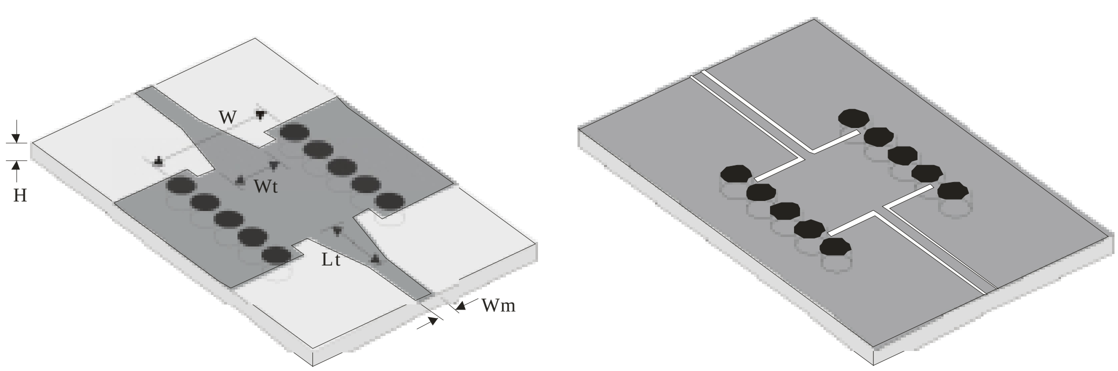
The rectangular waveguide is synthesized by placing two rows of metallized holes in the substrate, has illustrated in Fig. 2. The diameter D of the holes, the spacing b between the holes and the spacing W between the two rows are the physical parameters necessary for the design of the guide. The pitch b must be kept small to reduce the leakage loss between adjacent posts. However, the post diameter D is also subject to the loss problem. As a result, the ratio D/b is considered to be more critical than the pitch length because the post diameter and the pitch length are interrelated as shown in [7]. Due to the synthesis, the SIW can no longer be regarded as a normal homogeneous waveguide, and it is in fact an artificial periodic waveguide. Therefore, the post diameter may significantly affect the return loss of the waveguide section in view of its input port. Two design rules related to the post diameter and pitch that are used to neglect the radiation loss are formulated in [19]. These rules have been deducted from simulation results of different SIW geometries.

$$D < \lambda_g / 5$$
$$b \le 2D$$

These two rules are sufficient but not always necessary; a diameter larger than one fifth of guided wavelength or a pitch larger than two diameters can be used but with more care. These two rules ensure that the radiation loss be kept at a negligible level. In this case, the SIW can be modeled by a conventional rectangular waveguide (RW). Two different techniques have been applied to this end [19-20]. When following the two above rules, the mapping from the SIW to the RW is nearly perfect in all the single mode bandwidth. All the existing design procedures and theoretical frameworks developed for the rectangular waveguide are directly applicable to its synthesized counterpart. Nevertheless, dielectric filling effects and geometrical particularity of the synthesized waveguide should be accounted for coupler and antenna designs. In addition, the SIW can only support the TE modes propagation while the TM modes cannot be guided due to the nature of the structure.

B. SIW TRANSITIONS

SIW guide can easily be integrated with active devices because the design of transition between the SIW guide and the planar technology is straightforward. The first transition presented has involved a microstrip line [11]. The microstrip transition is a wideband structure, covering the entire useful bandwidth of the SIW guide. This transition structure makes use of a tapered microstrip line to excite the waveguide mode as illustrated in Fig. 3a. With low thickness substrate, the conductor loss in the waveguide section cannot be neglected and to reduce it, the thickness must be increased. This leads to an increase of radiation loss in the microstrip line that is not suitable for active component integration, in particular, at millimeter-wave frequencies.



(a) **(b)**

Fig. 3 – Integrated transitions from planar circuits to SIW guide: (a) Microstrip transition and (b) Coplanar waveguide (CPW) transition.

One way to overcome this problem is the use of a transition from coplanar waveguide (CPW) to SIW [21]. The CPW-SIW transition, as shown in Fig. 3b, consists of a coplanar waveguide section with 90° bend on each slot. A stub is added on the CPW line to match the transition and the rectangular waveguide is designed with via holes. However, this transition exhibits a narrower bandwidth compared to the microstrip counterpart. Of course, a wideband performance of CPW-SIW transition could be made possible.

C. SIW Circuit Examples

A number of applications using the SIW technology have been reported. Since this waveguide is a good candidate to design low cost filters, different topologies have been investigated. One of them is an offset inductive post SIW filter [7]. The filter is shown in Fig. 4a and provides a bandwidth of 1GHz with a center frequency of 28 GHz and an insertion loss of 1dB. Another is a dual-mode filter [22]. The filter provides 0.7 GHz bandwidth centered at 27.6 GHz. The insertion loss is about 1.8 dB in the middle of the band and the return loss is better than 20 dB over the entire pass band.

The SIW can also be used to realize resonator [6]. Current and voltage probes where developed to couple the resonator to microstrip line and CPW. An SIW resonator was used to design an oscillator at 12GHz [23]. Quality factor of 500 was obtained for the resonator constructed with a conventional substrate [6].

Another interesting SIW application is a low-cost and low-profile 1:N SIW power divider [9]. This divider can be used as power combiner for amplifier design or as feeder for antenna array. Fig. 4b shows a 1:16 divider with input/output microstrip interfaces. Using the SIW, a power splitting can be achieve at a much lower insertion loss compared to the planar circuit techniques. The design of this power splitter was based on existing rectangular waveguide techniques.

Finally we have also reported the realization of SIW directional couplers [8]. H-plane and E-plane types of the directional coupler have been designed and implemented, which have shown excellent performance over millimeter-wave frequency range. They are the important building blocks for more functional SIW circuits and systems such as the millimeter-wave six-port junction.

IV. Substrate Integrated Slab Waveguide (SISW)

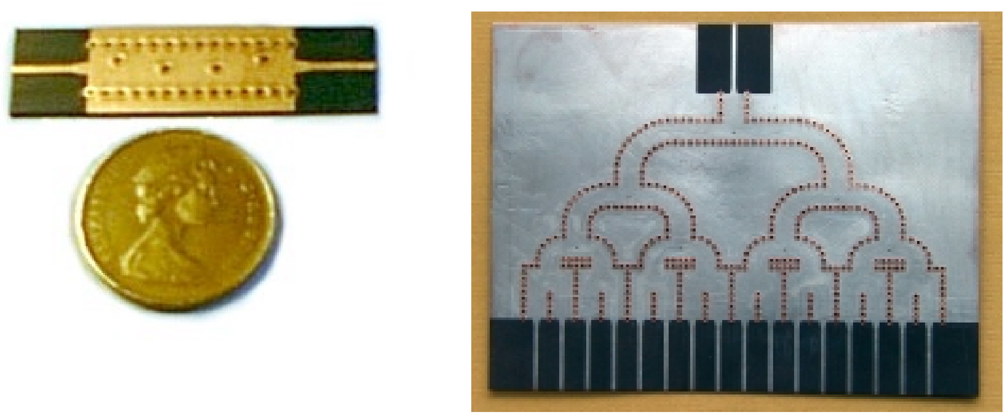
The slab waveguide has been known for its wide bandwidth when designed with a high permittivity dielectric slab. Using a dielectric permittivity of 5 for the slab, two conventional rectangular waveguide bands can simultaneously be covered with one single slab waveguide. This extended bandwidth can be useful to design frequency doublers or mixer, which may require wide bandwidth transmission line. Similar to the rectangular waveguide, the integration of this guide with planar circuits, however, requires a complex mechanical assembling. In the microwave range, the physical dimension of planar line and waveguide is quit different and some kind of tuning is usually necessary to achieve a good matching. These procedures would increase the cost of the overall system design.

With the SISW technique, the slab guide is synthesized on a substrate by adding air hole into an SIW. Fig. 1b illustrates the topology of the SISW guide. Using this technique, an SISW covering both X and Ku bands has been designed, realized and measured [12]. Back-to-back microstrip tapered line transitions similar to those used for the SIW (see Fig. 3a) were designed for measurement purpose.

V. Substrate Integrated NRD (SINRD) Guide

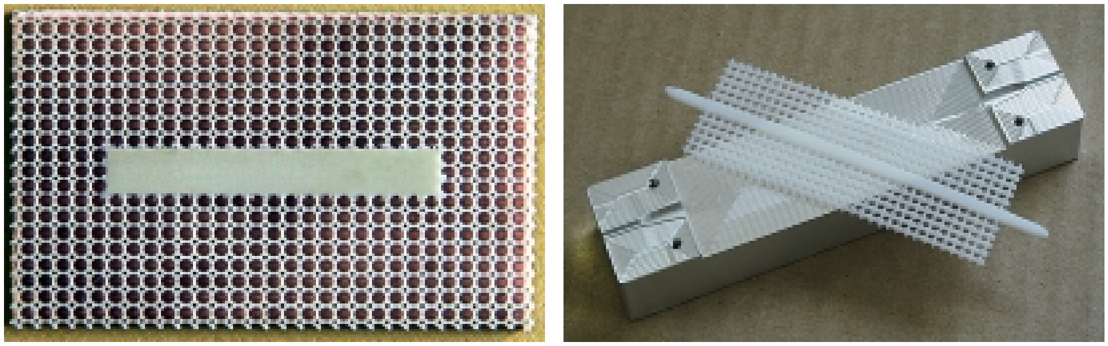
The NRD-guide [1] is a non-planar structure, and its basic geometry consists of three rectangular dielectric strips: two large identical ones with low dielectric value separated by a small one with a high dielectric value. The three strips are sandwiched between two metallic plates with spacing smaller than a half of guided wavelength (see Fig. 1c) in the low dielectric region. It was proposed to suppress the radiation loss inherent to a dielectric waveguide at its discontinuities.

In the SINRD guide, a periodic air hole pattern is used to effectively lower the dielectric constant of specific regions of a dielectric substrate, thus creating a wave-guiding dielectric channel in the substrate. Such a synthesized channel becomes



(a) **(b)**

Fig. 4 – Two practical SIW circuits examples: (a) an SIW Inductive post filter with microstrip transitions, and (b) an SIW 1:16 power divider with microstrip input/output interfaces.



(a) (b)

Fig. 5 – SINRD circuits: (a) A machined Cuflon SINRD circuit at 36GHz, which is laminated to a RT6002 0.254mm thick substrate on which the microstrip-to-SINRD transitions are etched. (b) SINRD circuit on Cuflon working at 80GHz with WR10 transitions.

a substrate integrated NRD guide or SINRD when the top and bottom of the substrate are closed with metallic planes. This is illustrated in Fig. 1c. Using this technique, complex NRD circuits can be built in one fabrication step without any manual handling. Furthermore, the dielectric substrate is sufficiently robust to allow its lamination with other planar substrate. In this way, the hybrid planar/NRD guide techniques can be made more cost-effectively and easily.

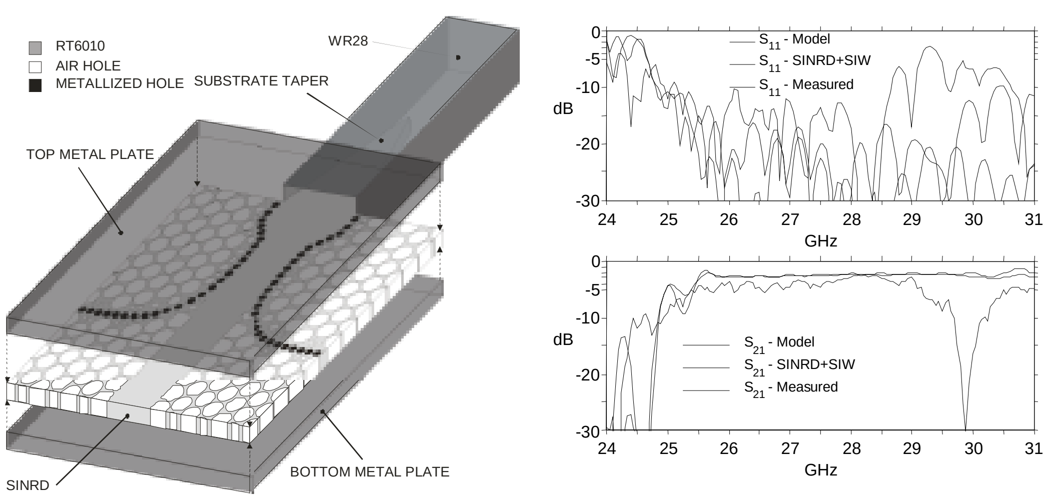
Similar to the technique presented above for the SIW, propagation analysis of the guide can also be made on the basis of the Floquet's theorem and this requires a 3D electromagnetic simulator [14,20] for the computation of S-parameters of the basic periodic cell. This analysis provides design information necessary to establish an equivalent NRD guide with regard to the SINRD, which is very useful in the design of circuits.

Simple circuits working at 30GHz, 36GHz [14] and 80GHz [13] were designed and built. Different types of transition were also made which mimic the existing type of NRD guide transitions [17,24-25]. Microstrip-to-NRD guide transitions, both for the LSM_{10} and LSE_{10} modes, were made in a hybrid SINRD/planar configuration. Also a WR10 to SINRD guide transition was realized for measurement purpose at 80GHz. Fig. 5 illustrates some of the realized circuits. These were used to verify the predicted propagation characteristics of the LSM_{10} and LSE_{10} modes inside the synthesized guide.

Some effort was also made in the realization of a substrate integrated WR28 to SINRD transition where both the SINRD and SIW structures are combined to yield interesting features. The transition was designed to work for the frequency range of 26GHz to 30GHz. Fig. 6 illustrates the studied integrated transition and provides the associated results. This merging or integration of the SINRD guide and SIW is still in the early development.

VI. SUBSTRATE INTEGRATED IMAGE DIELECTRIC GUIDE (SIIDG)

The SIC technique was also used in the experimental prototype of a dielectric resonator antenna array [10], each antenna being in fact an SIIDG resonator. The SIC advantages in this millimetre-wave antenna are mechanically robust



(a) (b)

Fig. 6 – Substrate integrated SINRD guide to WR28 waveguide transition: (a) topology of the transition where SINRD and SIW structures are combined together, and (b) simulation and measurement results of a back-to-back transitions arrangement.

because all of the small resonator elements are made of and fixed on the dielectric substrate, thereby reducing considerably the alignment problem of the resonators. In addition, the antenna array performances were shown to be equal or better than those of the conventional realization technique. Some electrical features such as gain control could easily be achieved by changing the air hole pattern dimensions.

VII. FUTURE DEVELOPMENT

In this section, we will briefly discuss on different avenues of the development in connection with SIC technologies.

Since the thin-film fabrication process can be used for the realization of SIC circuits, the use of nanotechnology can be now extended to SIC waveguides, which opens a whole new horizon in developing new and innovative devices and circuits. This is in particular important for millimetre-wave and submillimeter-wave applications. Fig. 7 shows a symbolic topology for an SINRD guide-based tunable phase shifter using barium strontium titanate (BST) ferroelectric material that may be made through nano-structured particles. The nano-structured substrate allows for significantly reducing the dielectric loss because the Eddy current that is responsible for high-frequency dielectric loss can be minimized at millimetre-wave frequency and beyond. In this topology, the proposed anode layout is made possible because the LSM10 mode in the SINRD guide is not affected by small transversal gap in the top or bottom metallic plane. A laser combined with a computer-controlled positioning system would machine the holes in the ceramic substrate. In addition, the base substrate may be synthesized by a nano-structured ferrite to realize a large number of tunable and ferrite devices.

Multilayer features of the LTCC fabrication process could be used advantageously for the SIC technology in the realization of compact wideband coupler, high-Q elliptic filter, etc. Naturally, the LTCC process would also be an excellent candidate for realizing a low-cost full-scale SIC-based millimeter wave transceiver.

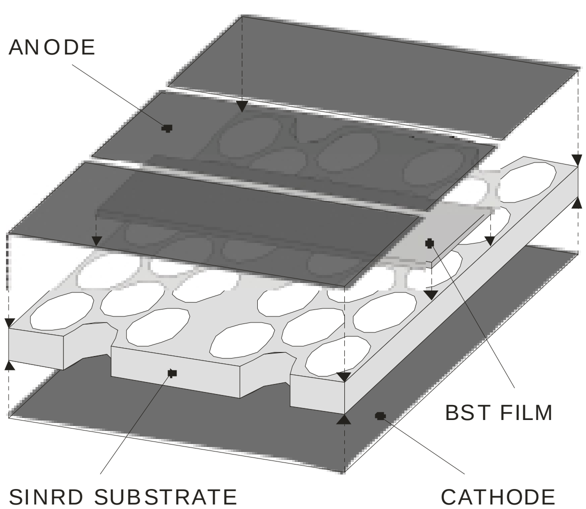


Fig. 7 – Topology of a thin-film SINRD guide phase shifter.

Since the SIC scheme heavily deals with the substrate properties and substrate volume, this can be exploited for electro-optical device applications such as electro-optical modulators and photo-detectors if the substrate can be used simultaneously electrically and optically. This can used to design optically controlled electrical circuits or vice-versa. This type of circuits can be used to design future millimetre-wave system-on-chips (SOC) if nonlinear and active SICs are developed in monolithic integration with passive SICs.

VIII. CONCLUSIONS

This paper presents an overview of the current substrate integrated circuits (SICs) development with a number of practical examples. Technical features of this new generation of microwave integrated circuits are demonstrated with design rules and circuit performance. Mechanical and electrical properties are discussed in detail with reference to various SIC platforms. Future trends are also indicated with emphasis on the development of future low-cost and high-performance millimetre-wave, submillimeter-wave and optoelectronic applications. It is believed that this new concept will fundamentally change the landscape of our high-frequency research and development.

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