Recent Advances of Hybrid Planar/NRD-Guide Technology for Millimeter-Wave Integrated Circuit Design

Ke Wu, Yves Cassivi

Abstract - **In this paper, we look at different possibilities and advantages of our early proposed hybrid planar and non-radiative dielectric (NRD) guide technology in the design of various millimeter-wave circuits. First of all, an overview of the NRD guide technology progress is presented. It indicates that the hybrid planar/NRD-guide (HP/NRDG) technology provides a straightforward assembly of MMIC circuits with NRD-guide. To begin with, a simple fabrication technique for NRD-guide is described, which allows the fabrication of complex NRD circuits in a single step. Then, a new magic tee junction based on HP/NRDG technology is presented with measured results. New mode suppressor topologies compatible with the HP/NRDG technology are discussed for spurious waveguide modes, the LSE_{10} mode and also the LSM_{10} mode. Finally a discussion is made on different design possibilities of HP/NRDG power amplifier topologies. The present overview of some of our ongoing research work on the HP/NRDG technology suggests that the realization of a low-cost millimeter-wave transceiver is possible.**

I. INTRODUCTION

Since the introduction of the NRD guide (see Fig. 1) by Yoneyama and Nishida [1], much effort has been made in the development of millimeter-wave components based on this technology. Today, NRD guide based filters [2,3], antennas [4,5,6], circulator [7], coupler [8], terminator [9], Gunn oscillator [10], amplifier [11] and amplitude modulator [12] are available. The design of those components rests on the LSM_{10} mode that provides low loss properties.

Also this mode can easily be excited by a rectangular waveguide transition [13]. However, the NRD guide is a multimode structure where, beside the LSMmn modes, LSEmn modes can also propagate. In fact, the LSE00 and LSE10 modes will have lower cutoff frequencies than the LSM10 mode. Because of the electrical nature of the LSM10 and LSE10 modes, a modal conversion between those two modes is possible along bend, misalignment or asymmetry of the NRD guide [14,15]. This phenomenon may generate some resonance problem in NRD guide circuits [14]. To solve this problem, an LSE10 mode suppressor was developed [7,16], which greatly improves the performance of certain circuits.

Authors are with Poly-Grames Research Center, Département de Génie Électrique,École Polytechnique de Montréal, C.P. 6079, Succ. Centre-Ville Montréal, Québec, Canada H3C 3A7
wuke@grmes.polymtl.ca, cassivy@grmes.polymtl.ca

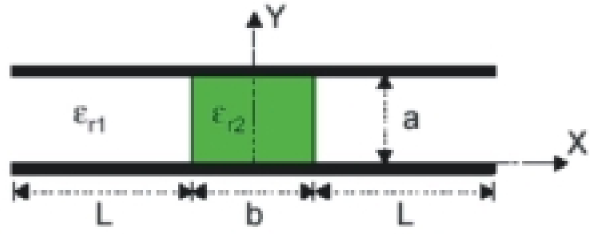

Fig. 1 – NRD-guide cross-section

Some effort was also made in the integration of those circuits to form practical systems. The first example is a high-speed ASK transceiver at 60GHz [17]. This radio is capable of transmitting a data rate higher than 400Mb/s with a receiver sensitivity of –40dBm. This transceiver involves a Gunn oscillator, couplers, circulators, a mixer and a ASK modulator. Another example of NRD integration is a FM-CW radar for motor vehicle [18]. This radar was able to detect obstacle at a distance of 47 meters.

But even if the obtained performance of these devices is promising, the advantages of low cost usually associated with NRD guide do not always look feasible because of the complex 3D assembly arrangement of those devices. Low cost can only be realized if automation is possible in the fabrication of the elements and in the assembly of the device while the reliability and yield can be guaranteed.

To overcome these difficulties, a hybrid integration technology of planar circuits and NRD-guide (HP/NRDG) was introduced [19]. This technology is based on the mechanism of coupling a planar circuit to an NRD guide using a multilayer approach that has been found very effective. Many types of planar transition between planar circuits such as microstrip line [20,21], coplanar waveguide [22] and slotline [23] have been developed so far. The main advantage of these transitions is that both the LSM10 and LSE10 modes can be excited, depending on the geometrical orientation of the NRD guide in the transition.

So this technology provides the platform necessary to facilitate the combination of MMIC component with an NRD guide. For example, an HEMT oscillator with a multiple-ring NRD resonator feedback circuit was designed [24]. And also analytical equations for the analysis of such circuit were developed in [25]. Unfortunately, this hybrid arrangement has its own inconvenience. Due to the geometrical asymmetry, the planar to NRD guide transition may excite not only the LSM10 mode (or LSE10 mode) but also other spurious waveguide modes, which could degrade circuit performance. Furthermore, an LSE10 mode suppressor compatible with this technology is still needed to provide a viable low cost technology for millimeter-wave transceiver realization.

In this paper, the advantages and the flexibility of this HP/NRDG technology will be illustrated by describing some recent advances in this field. Some solutions for the previously mentioned problems are presented. So, we begin with a brief description of a new NRD guide fabrication technique called engraved NRD (ENRD) guide that eases the construction of complex NRD guide circuits. Next we present a new magic tee junction topology based on the HP/NRDG technology. This circuit is a good example showing potentials of the technology. Different mode suppressor topologies will be discussed for handling spurious waveguide modes and LSE10/LSM10 modes. Finally, different topology possibilities for HP/NRDG power amplifier circuits are discussed.

II. ENGRAVED NRD FABRICATION TECHNIQUE

In this section, we discuss a new type of NRD-guide structure called “Engraved NRD-guide (ENRD)” that can significantly alleviate the problem of alignment and mechanical tolerances in NRD circuit fabrication, especially in the use of hybrid integrated planar NRD-guide technology. This new scheme of design was very briefly presented in [26] and is described in greater detail in [27]. The ENRD guide is made of a single dielectric block with a metal plate glued on one side for strength. By machining the dielectric block, only a necessary amount of dielectric part is removed from the block so to form an equivalent NRD-guide that has almost the same propagation constant. The remaining part of the dielectric block is kept in support of the cover, which could be a microstrip line substrate as illustrated in Fig. 2. The principal design parameter of an ENRD guide is the gap dimension.

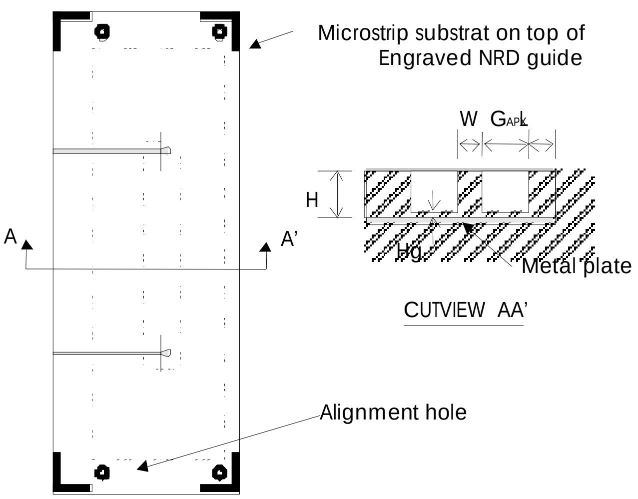

Fig. 2 - ENRD guide topology

Many NRD circuits were made using this technique, such as filter, 90° corner, T-junction and magic tee. As an example, Fig. 3 illustrates the topology of an ENRD filter and Fig. 4 gives the measurement results for this filter with two different gap values in addition to the simulation results.

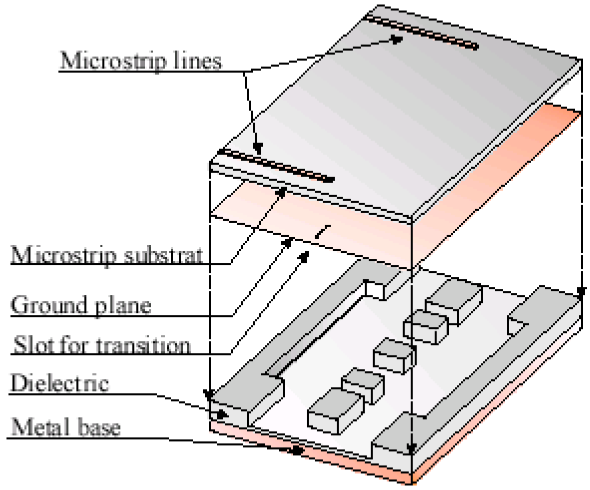

Fig. 3 – Topology of an ENRD guide filter

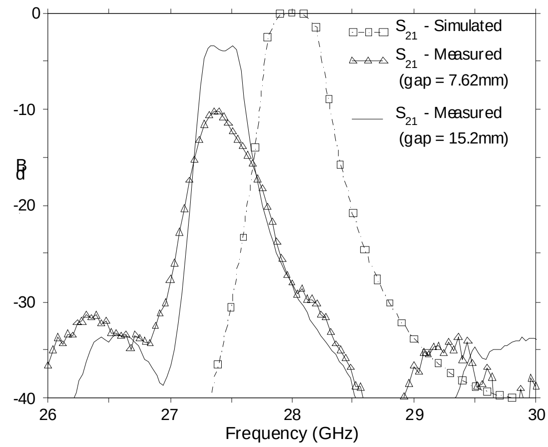

Fig. 4 – Simulation and measurement results of S_{21} for an ENRD guide filter.

III. HP/NRDG MAGIC TEE JUNCTION

Fig. 5 shows the topology of the HP/NRDG magic tee junction [28]. The new magic tee is composed of an NRD-guide LSM10-to-LSE10 T-junction, which is used as a difference port, and a microstrip junction used as a sum port. The microstrip T-junction and the NRD-guide T-junction are combined with two microstrip-to-NRD-guide LSE10 mode transitions [20]. The two transitions are placed over the two output branches of the NRD-guide T-junction. So the microstrip T-junction produces two in-phase LSE10 mode signals inside the output branches of the NRD-guide T-junction. Since such two signals are in phase, they cannot produce an LSM10 mode signal at the difference port, contributing to a good isolation of the sum and difference ports. Similarly, the out-of-phase LSE10 mode output signals produced by the NRD-guide T-junction generate a virtual short circuit at the center of the microstrip T-junction of the sum port, which also contributes to a good isolation between the two ports

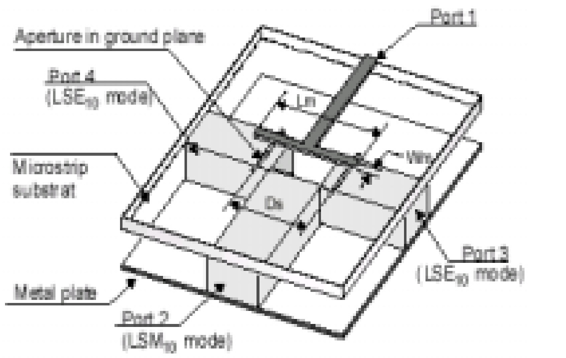

Fig. 5 – Topology of the HP/NRDG magic tee junction

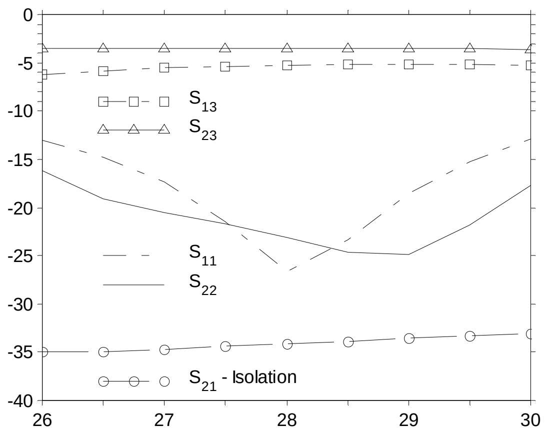

Fig. 6 – Simulation results for the magic tee junction.

Fig. 6 gives the simulation results of the magic tee junction. The isolation level obtained is good, but we see a difference between S13 and S23. The difference is caused by the LSE10 type microstrip-to-NRD-guide transitions used in the sum port.

To measure the proposed magic tee, appropriate microstrip-to-NRD-guide transitions are added to ports 2, 3 and 4. So all the ports of the magic tee are related to microstrip lines and a conventional two-port vector network analyzer can be used in combination with a test fixture and a microstrip line TRL calibration, as well as a matrix technique [29] to measure the 4 ports scattering matrix of the magic tee device. Note that because there is no NRD-guide TRL kit available, effects of the microstrip-to-NRD transitions have to be added in the measurements. The NRD-guide magic tee was constructed using our developed ENRD fabrication technique. A gap of 7.62mm was used in the fabrication.

Measured results of this structure show a number of spikes. This is similar to the case explained by Yoneyama and his co-worker [14] where spikes appear when an NRD-guide bend is terminated by LSM10 mode waveguide transitions. That construction results in an LSE10 mode cavity having resonance at discrete frequencies. At resonance, the LSE10 mode signal, which is linked to the LSM10 mode signal through mode conversion, cannot propagate in the structure, resulting in a high insertion loss for the LSM10 mode at these frequencies.

For the hybrid NRD-guide magic tee, the spikes are the result of two separate resonance paths. An LSM10 mode load was added in each output braches of the junction to reduce the effect of those resonances. Measured results of the modify device are presented in Fig. 7.

IV. HP/NRDG Mode Suppressors

Here we present two types of mode suppressors. The first is for the spurious waveguide modes that can propagate in a closed NRD guide. The second is a topology of mode suppressor that can work for LSE10 mode or LSM10 mode, depending on the orientation of the aperture used in the metal plane of the guide.

A – *Spurious Mode Suppressor*

For the HP/NRDG technology, the NRD waveguide is coupled to a planar geometry, e.g., microstrip lines for achieving a compact 3-D circuit design with the two dissimilar structures. Many types of transitions have been developed [20,21] for this purpose. However, these transitions are usually asymmetric relative to the vertical orientation of the NRD-guide. This asymmetry is usually the major cause of parasitic modes excitation because a symmetry magnetic wall is not enforced in the center of the NRD-guide. So a transition designed to excite the wanted LSM10 mode is prone to generate parasitic modes such as the TE02 waveguide mode. In the case of a transition designed to excite the LSE10 mode, the main excited parasitic modes is the LSE00 (or TE01) mode, in addition to other secondary spurious modes. Since an NRD filter designed for the LSM10 mode operation does not behave in the same way for other modes propagating in the structure, the parasitic modes caused by the transition could pass though the filter without being attenuated. This leads to a reduction in the effective out-of-the-band rejection level of the filter.

To resolve this problem, a waveguide type mode suppressor was introduced by Tang et al. [30,31]. This mode suppressor is integrated with the LSM10 mode type transition and suppresses all the spurious modes except the LSM10 mode. This device help improve the performance of the NRD filter. Nevertheless, the problem associated with this mode suppressor lies in its fabrication as well as the undesired overall size of the circuit.

The HP/NRDG technology allows the direct use of uniplanar compact electromagnetic bandgap (UC-EBG) periodic structure [32] printed on one or both of the metallic plane of the NRD guide to suppress the low order parasitic waveguide modes that are excited by the microstrip-to-NRD-guide LSM10 mode transition. This technique eliminates the fabrication and size problems as encountered in the waveguide type mode suppressor

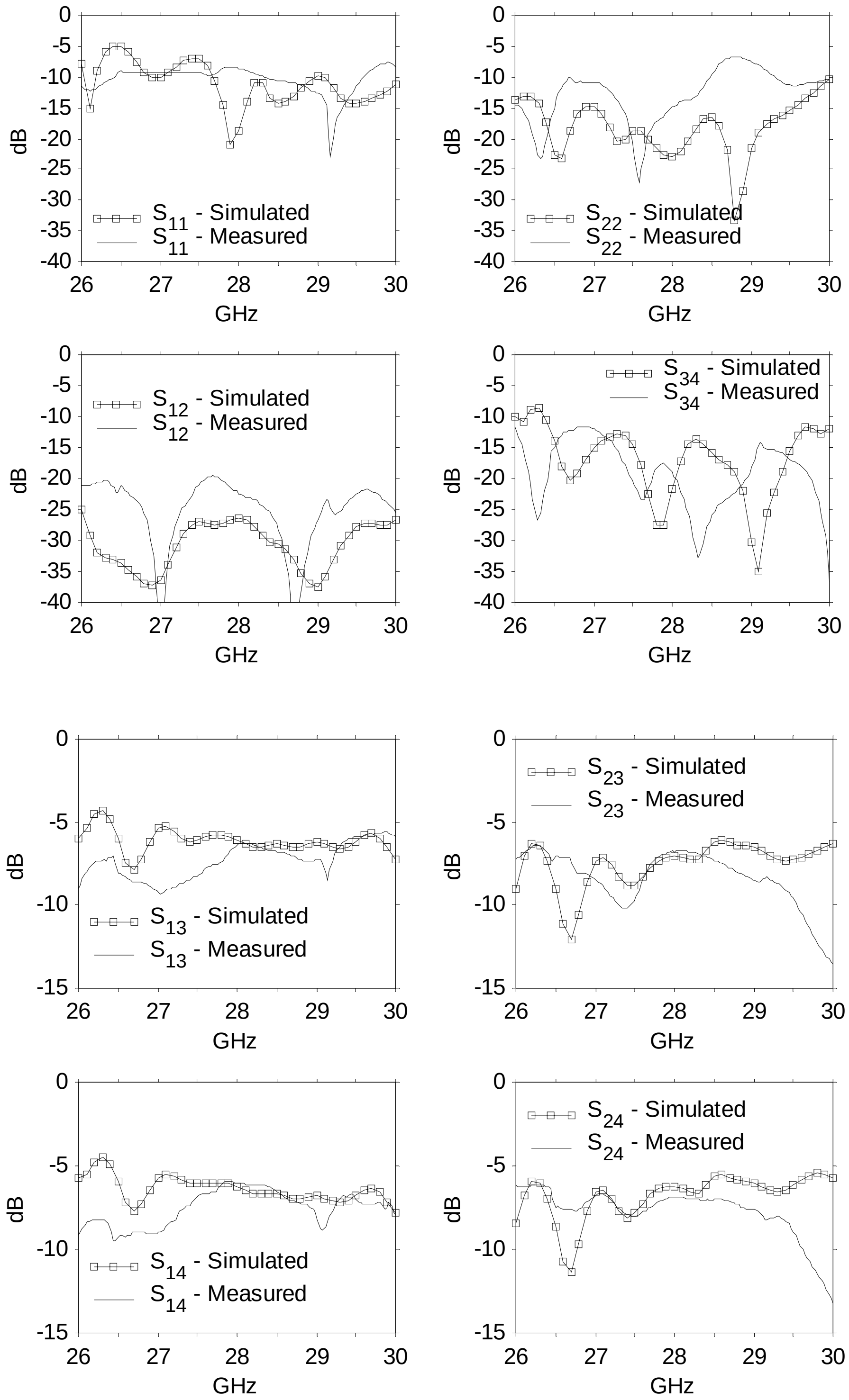

Fig. 7 – Measurement results with the corresponding simulation results, which included the LSM10 mode loads and the microstrip-to-NRD-guide transitions.

The proposed mode suppressor consists of an UC-EBG periodic structure etched on a dielectric substrate that will serve as one of the two metal planes of the NRD guide. The structure can be made symmetrical by replacing both metal planes by UC-EBG periodic structure. The UC-EBG cells cover the region from the metallic sidewalls of the guide up to a distance WM from the dielectric slab of the NRD as shown in Fig. 8. The distance WM is adjusted so to obtain the maximum attenuation of the parasitic modes without affecting the LSM10 mode. But no UC-EBG cells are placed near the transition because it can be affected considerably by these cells. Note that this suppression method is not sufficient for LSE10 type microstrip-to-NRD-guidec transition since the LSE00 mode that always has a smaller cutoff frequency than the LSE10 mode, is also excited by the transition.

Furthermore, the LSE00 mode has an electrical field profile normal to the metal plane of the NRD guide, which is almost identical to the LSE10 mode. So it is not possible to distinguish both modes easily. In this case, a symmetrical transition needs to be used. This transition would enforce the magnetic symmetry plane between the two metal planes, reducing considerably the excitation of the LSE00 mode. But this is subject of our further work. Fig. 9 gives measurement results of an NRD guide filter with and without an asymmetric spurious mode suppressor. It clearly shows the increase of out of band rejection of the designed filter.

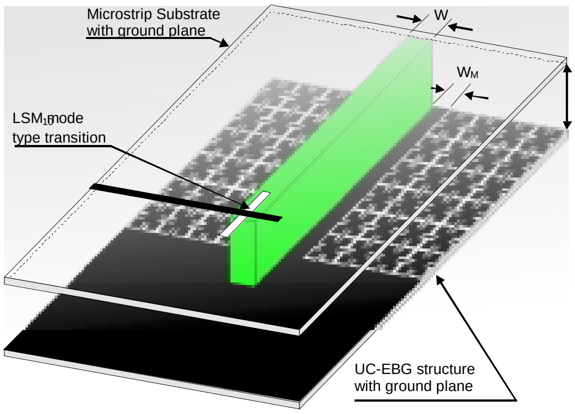

Fig. 8 – Topology of an asymmetric spurious waveguide mode suppressor

B – *LSE$_{10}$ Mode/LSM$_{10}$ mode Suppressor*

A LSE10 mode suppressor as already been developed by Yoneyama and al. [7,16]. It consist of a metallic plane etched on a fine metal sheet that is place inside the dielectric slab of the NRD guide, and oriented along the direction of the electric field of the LSE10 mode. This mode suppressor was proved necessary in many devices because of mode conversion exciting in NRD structures, and provide very good performance. But the assembly of this suppressor is rather difficult.

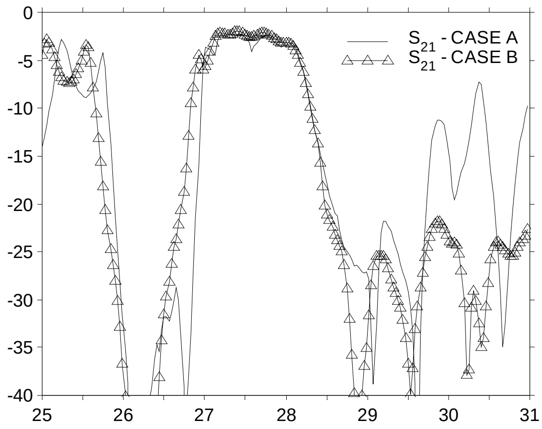

Fig. 9 – Measured results for an NRD guide filter:
Case A: with the mode suppressor
Case B: with an asymmetric mode suppressor

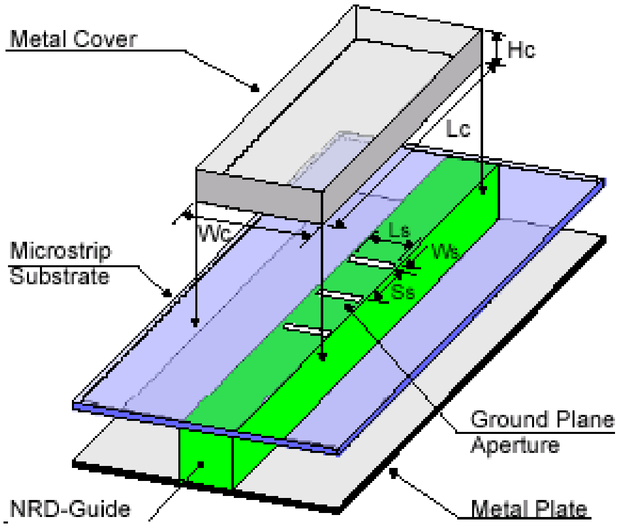

Fig. 10 – Topology of an LSE$_{10}$ mode suppressor

In the proposed mode suppressor, one mode is coupled to a rectangular cavity via transversal or longitudinal apertures, depending on whether the LSE10 mode or the LSM10 mode is to be suppressed. The cavity with apertures forms in fact a wideband stopband filter suitable for mode suppression. Fig. 10 provides an example of LSE10 mode suppressor topology. The metal cover is the cavity and the aperture are etched from the ground plane of a microstrip substrate, making the suppressor compatible with HP/NRDG technology. The simulation results for the LSE10 mode suppressor are given in Fig. 11. It shows that the LSM10 mode is not affected by the circuit and that a rejection of more than 10dB is obtained over a 4GHz bandwidth is possible. Note that this suppressor is still in the development stage.

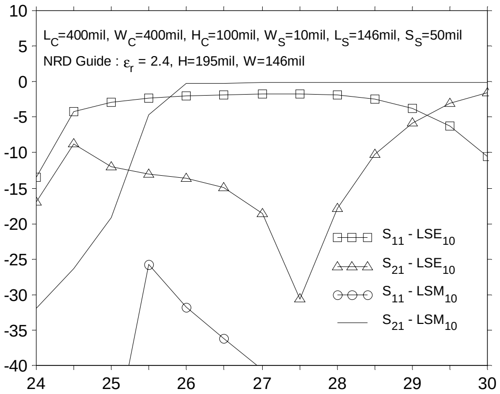

Fig. 11 – Simulation results for the LSE_{10} mode suppressor

V. HP/NRDG Power Amplifier

The next step in the research is the development of a HP/NRDG based power amplifier. The simplest topology is to combine a MMIC power amplifier die to an NRD guide via an input and an output planar-to-NRD-guide transitions. This arrangement would give a total gain about 2dB lower and a P1dB 1dB lower than the gain and P1db of the MMIC amplifier because of the loss in the transitions. Using the previously described magic tee junction, a balanced amplifier configuration providing enhanced return loss and P1db level is possible.

As discussed in a previous section, however, an LSE10 type transition between a planar circuit and a NRD guide also excites the LSE00 mode, which increases the insertion loss level of the transition. In this application it is possible to use symmetric LSE10 type transitions in the magic tee that has one aperture on the ground layer of the top PCB and another aperture on the ground layer of the bottom PCB. Here both PCBs serve as the metallic planes of the NRD guide and also as the support for the MMIC amplifiers. Thermal consideration can be resolved by placing a metal block between the two NRD guide T-junction. This block also helps to electrically isolate the input magic tee junction from the output junction. So this arrangement can efficiently combine four MMIC power amplifiers as illustrated in Fig. 12 and would provide the much-needed high P1db for high capacity communication services.

VI. Conclusions And Future Work

Some recent advances in connection with the hybrid planar and non-radiative dielectric (NRD) guide technology are presented and discussed. This technology allows the realization of a large number of millimeter-wave circuits such as magic tee junctions, oscillators, mode suppressors and power amplifiers using simple multilayer like topologies. With the use of the ENRD fabrication technique, it would help reduce the cost of millimeter-wave transceiver as compared to the conventional rectangular waveguide technique.

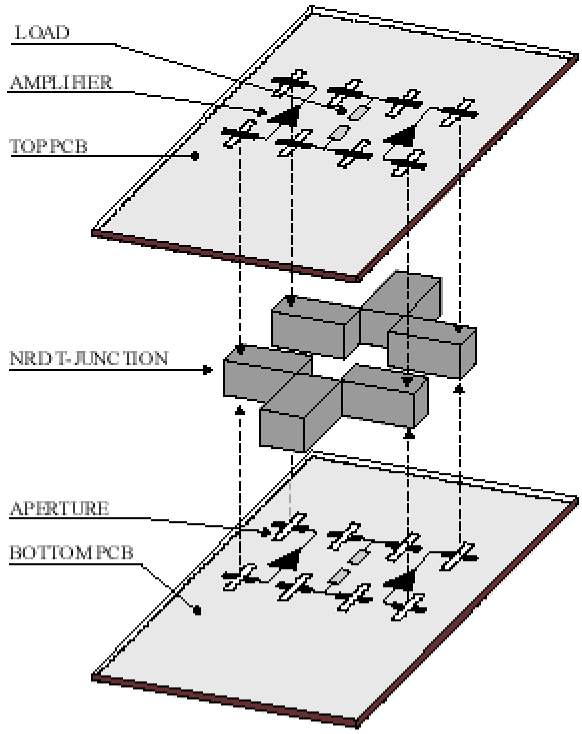

Fig. 12 – Topology of an HP/NRDG balanced power amplifier combining four MMIC amplifiers.

Our research activity will now focus on the integration of these circuits in a HP/NRDG based transceiver for the local multipoint distribution system (LMDS or LMCS in Canada) working between 27GHz and 31GHz, as well as for millimeter-wave sensor applications.

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