GUIDED-WAVE PROPERTIES OF SYNTHESIZED NON-RADIATIVE DIELECTRIC WAVEGUIDE FOR SUBSTRATE INTEGRATED CIRCUITS (SICS)

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***Abstract* -- This paper presents the very first investigation of guided-wave properties of a non-radiative dielectric (NRD) guide synthesized on a single substrate for the design of substrate integrated circuits (SICs). The synthesis of the new NRD-guide is made possible by removing part of the substrate or by punching hole or slot arrays that results in two separate lower dielectric-constant regions to which the core NRD strip is bounded. A mode-matching technique is applied to model this guided-wave problem that takes into account various parametric effects of geometry. Propagation constant, leakage loss and modal characteristics are studied for the synthesized NRD-guide structure. Our results show that a synthesized NRD-guide can effectively be co-designed with planar circuits based on the same substrate to form a new class of integrated circuits called "substrate integrated circuits" (SICs). This work is useful for the development of low-cost and high-density millimeter-wave ICs.**

I. INTRODUCTION

Searching for low-cost, high-performance and high-yield millimeter-wave RF technologies generally demands a high-degree of circuit block integration in connection with design technique and manufacturing process. The planar structure still presents the mainstream of design preference for millimeter-wave integrated circuits (ICs) and systems.

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 required to remedy such a problem, and thus the hybrid 2-D and 3-D schemes of planar and non-planar structures become attractive.

We have presented various hybrid design platforms that effectively combine the planar circuits and non-radiative dielectric (NRD) waveguide for millimeter-wave applications. The NRD-guide [1] may be regarded as a non-planar structure, and its basic geometry consists of a rectangular dielectric strip sandwiched between two metallic plates (or planes) with spacing smaller than a half of free-space wavelength. Our proposed design strategies of hybrid planar circuit/NRD-guide offer a unique possibility of exploiting complementary advantages of each individual building block while eliminating (at least partly if not completely) inherent drawbacks [2-5]. Essentially, two basic platforms of hybrid integration may be considered [6], namely, (A) aperture coupling-based hybrid integration techniques (HITs), and (B) co-layered hybrid integration techniques.

Several fundamental conditions should be satisfied in the design of NRD-guide that include the spacing between the two metallic planes of the NRD-guide and an adequate modal transfer between the two structures if the hybrid architecture of planar circuit and NRD-guide is involved. If the outer section of the core NRD-guiding part is filled up with a dielectric material instead of air and this material has a dielectric constant lower than that of the NRD-guide strip, the non-radiating condition can still be preserved as long as the spacing is smaller than a half of the guiding wavelength relative to that dielectric material.

In this way, the spacing between the two metallic planes may be significantly reduced, and a composite thick inhomogeneous NRD-guide layer is thus formed, which is called "Channelized NRD-guide" [14]. Interesting features of this new NRD-guide have been presented in [6, 14-16]. In particular, the channelized NRD-guide may allow propagation of the two fundamental modes having a comparable transmission loss, and in some cases the LSE mode may even become the lowest loss mode.

In this paper, we will show and study a possibility of creating a channelized NRD-guide within a single

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dielectric substrate or wafer that has an adequate thickness and a contrast (or ratio) of the dielectric constant between the channel part and its outer surrounding area.

II. Synthesized NRD-Guide

The channelized NRD-guide can be made through two basic approaches of synthesis. The first approach is to artificially synthesize the substrate with equivalently low and high dielectric regions according to the design rule of the channelized NRD-guide. We can, for example, punch arrays of air hole or slot on a high-frequency dielectric substrate (low loss ceramic, e.g.), where an equivalent dielectric constant lower than the inherent one can be expected. The synthesized substrate can then be used to design all types of hybrid planar/NRD-guide circuits.

The second approach may deal with semiconductor substrate (wafer) in which the channelized NRD-guide can be formed with some "material doping" techniques, or even it can be induced. In addition, active circuits can be designed and monolithically fabricated on the same wafer. In fact, nano- and micro-fabrication techniques may be applied to the design of the synthesized NRD-guide, which may involve a number of interesting features including tunable anisotropic electric/magnetic substrate and nonlinear effects. This will also lead to a potentially low-cost monolithic integration of planar and NRD-guide circuits. The proposed approaches are of course multilayer-compatible. This concept of high-frequency ICs may be termed as "substrate integrated circuits (or SICs)", which is to highlight the role of substrate in the hybrid design of the planar and non-planar structures.

In this following, we will present some aspects of the guided-wave properties of the synthesized NRD-guide based on the first approach discussed above.

III. Basic Guided-Wave Features

The new NRD-guide is designed and synthesized with two separate air slot or hole arrays (the term of "hole" will be used in the following) that are punched along two separate cross-sectional regions on a substrate and thus the NRD-guide is formed by the dielectric strip block between the two regions where a lower dielectric constant is expected due to the punched hole arrays. The synthesized NRD-guide is supposed to have infinite extent along the propagation direction. The objective of this very first investigation is to identify the number of holes required for designing an NRD-guide as well as some basic guided properties related to geometric parameters with emphasis on the leakage properties.

Our modeling technique of such a composite structure is based on a mode-matching technique that allows the field expansions in all of the subregions, and the two fundamental modes, namely, LSE_{10} and LSM_{10}, can be calculated. Details of this approach has been already presented elsewhere [17].

Fig. 1 describes a parametric convergence behavior of the normalized propagation constants at 28 GHz for the two fundamental (useful) modes as a function of the number of air hole used to construct the synthesized NRD-guide, including the cross-section view of the basic geometry (only a half of the cross section of the structure is shown for its electrical and magnetic symmetry depending on the mode of interest). It is found that the propagation constants are effectively stabilized as long as the number of holes is increased beyond 3. In addition, the hole size is also shown to be important to achieve a convergence.

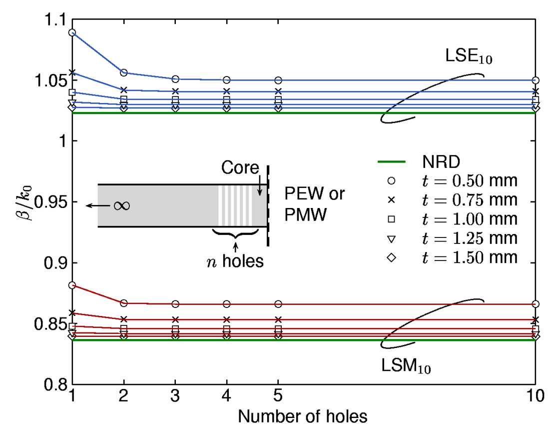

Fig. 1: Normalized propagation constant of LSE_{10} and LSM_{10} as well as convergence behavior of the synthesized structure versus the number of hole.

Normally, a large hole size yields a better convergence of the synthesized waveguiding effects. This is because the non-radiative condition can be guaranteed in a larger artificial dielectric contrast, which corresponds to the case of larger air hole. Nevertheless, the effective dielectric constant obtained in the outer regions will in turn determine the spacing between the two parallel plates or the substrate thickness. To design a non-radiative structure, the leakage effect should also be studied.

Fig. 2 shows an interesting scenario of the synthesis in which how the bulky or leaky-wave substrate can gradually become a non-radiative dielectric waveguide from the prospective of leakage. It is found that the leakage can be reduced down to 10e-15 dB/cm once 6 holes are used to design the structure. It is expected that 7 and 8 holes will lead to a completely negligible leakage loss and this is why the two resulting curves become abnormal due to the limited numerical accuracy involved

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in the calculations (out of the computational window for the leakage loss calculations). Note that the hole size is set to be 1.25 mm in this case. Similar behavior can be expected for other hole sizes.

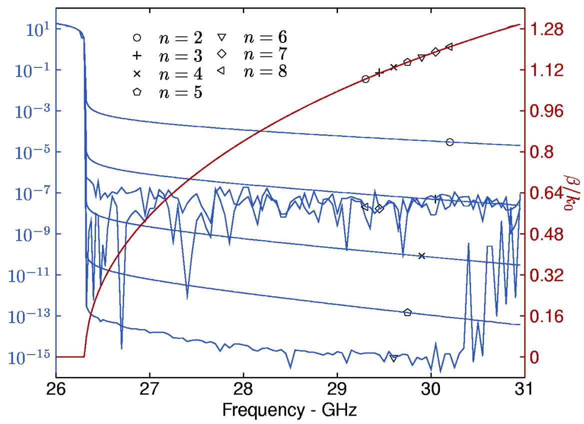

Fig. 2: Leakage and propagation properties of a synthesized NRD-guide.

In addition, the typical dispersion characteristics of the fundamental mode including the cut-off features can be observed in the results. It can be seen that the propagation constants are hardly affected by the number of holes.

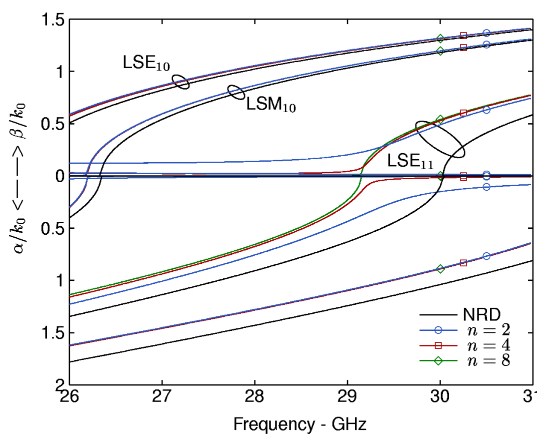

Fig. 3: Dispersion diagram of the fundamental and first higher-order modes.

As shown in Fig. 3, dispersion properties of the fundamental and higher-order modes of a synthesized NRD-guide can be calculated even for the case of a large leakage (the hole size is 0.5 mm in this case). The effect of the number of hole can also be seen in the figure. Interestingly, a modal conversion of leakage to guidance is observed and it can be described in Fig. 3 from the radiating state to non-radiating state once the number of hole is increased from 2 to 8. This is also applicable to LSE_{11} mode and other higher-order modes.

Fig. 4 illustrates the electric (top) and magnetic (bottom) fields profile of LSM_{10} mode in the presence of a leakage (2 holes are used in the calculation). It can be seen that the LSM_{10} mode is clearly formed with a visible leakage of fields over the cross-section of the structure. This is consistent with the results presented in Fig. 2. It can be expected that a complete non-radiative LSM_{10} mode is formed once the number of holes is increased beyond 6.

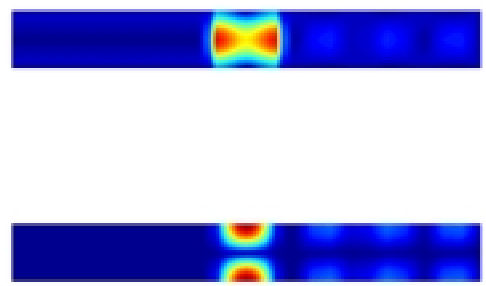

Fig. 4: Plot of electric (top) and magnetic (bottom) fields generated for LSM_{10} mode with 2 holes.

Typical frequency-dependent leakage and propagation characteristics of the fundamental LSM_{10} mode with respect to the size of hole are depicted in Fig. 5, for which 4 holes are used in the calculations. Two observations can be made here.

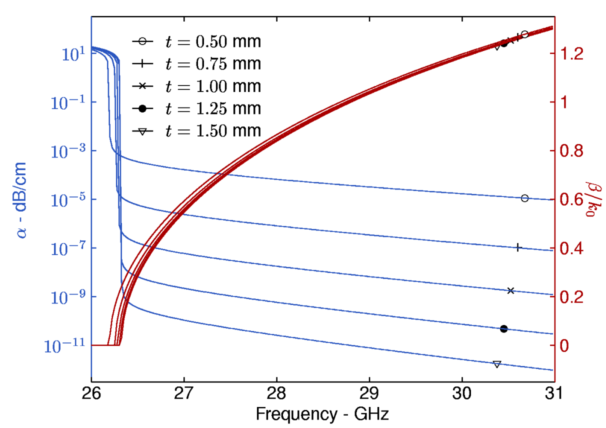

Fig. 5: Leakage and guidance properties of the fundamental LSM_{10} mode as a function of the size of hole in the case of 4 holes.

First, the cut-off frequency may be slightly alternated by the size of hole while the basic propagation properties remain almost intact. This is easily explained by the fact that the change in size will modify the effective dielectric constant of the synthesized regions thus the dielectric contrast of the core dielectric strip and surrounding areas.

Second, the leakage loss is monotonically reduced with the increasing size of hole. Obviously, such a leakage may become negligible once it exceeds the pre-designated value such as 10e-7 dB/cm or so. This can be expected because the contrast of the dielectric constant between the two regions becomes larger with larger hole, and the fields are more confined within the core strip region. Nevertheless, there are other issues that have to be considered in the design of the synthesized NRD-guide such as the choice of thickness of the substrate and mono-mode bandwidth.

In addition, design considerations should also involve the design aspects of planar circuits that use the same substrate such as the achievable impedance level and higher order mode propagation problems. The choice of the planar line is important for the design of hybrid integrated planar/NRD-guide circuits or substrate integrated circuits (SICs). To some extent, the proposed SICs scheme involves only dual-purpose planar topologies (planar and NRD circuits) that are massively producible.

IV. CONCLUSION

We have presented and discussed guided-wave features of synthesized NRD-guide for the design of substrate integrated circuits (SICs). It is found that a small number of hole is required to achieve low or negligible leakage loss level and stable modal profile. The mechanism of the NRD-guide synthesis has been presented with a number of numerical results, which show the modal conversion from leakage to non-radiating guidance. Our work indicates that a conventional substrate may be synthesized to create an on-substrate NRD-guide that becomes an inseparable integrated part of the planar circuits. This suggests that the concept of "substrate integrated circuits (SICs)" can be anticipated for future designs of low-cost millimeter-wave ICs and systems.

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