Leakage and Guidance Properties of Unbalanced Insulated NRD-Guide for Co-Layered Integrated Circuits

Ping Yang, Duochuan Li, Ke Wu

Poly-Grames Research Center
Department of Electrical Engineering
École Polytechnique de Montréal
Montréal, Québec, Canada H3C 3A7

Abstract — **Leakage and guidance characteristics of unbalanced insulated NRD-guide were studied by means of a mode-matching technique. Leakage suppressing condition and single mode operating condition are investigated for practical applications and the relations between geometrical parameters of the structure and the guided wave as well as leakage properties were obtained. Extensive results and useful guidelines were provided for practical application of this guided-wave structure in co-layered integration circuits.**

I. Introduction

Co-layered hybrid integration techniques based on NRD-guide and planar circuits become attractive for use in the design of millimeter-wave integrated circuits [1]. In this co-layered topology, the planar circuits are in direct physical contact with the NRD-guide, thus yielding a strong electromagnetic coupling between the two dissimilar structures. Very compact transitions can be designed with broadband features. However, leakage may also manifest in this structure because of potentially asymmetrical dielectric substrates. Therefore, how to suppress the leakage is critical to practical applications of this hybrid integrated structure.

This co-layered hybrid integration structure may actually form an insulated NRD-guide proposed by T.Yoneyama et al. [2]. In [2], propagation properties of the insulated NRD-guide were studied by means of EDC approach, but the phenomenon of leakage was not discussed as it was basically used for low loss guided-wave applications without considering the hybrid scheme of planar and NRD-guide circuits. Tang et al. [3] have analyzed characteristics related to the leakage of this structure and presented some pertinent physical effects such as leakage and resonance. However, there are missing information in connection with the impact of leakage on the bandwidth of single operating mode. In this paper, we emphasize on investigation of the leakage condition by means of a mode-matching technique, therefore providing useful guidelines for deploying this co-layered hybrid platform in various millimeter-wave integrated circuits design.

II. Analysis and Numerical Results

To begin with, we consider this co-layered structure as an unbalanced insulated NRD-guide. Fig. 1 shows the cross section of this guided-wave structure. According to the symmetry in x-direction, we can put one perfect electrical plane at x=0 and therefore simplify our following analysis. By applying a mode-matching approach, we can readily obtain the propagation properties of this unbalanced or generalized insulated NRD-guide.

A. Non-radiative Condition

From Fig. 1, we can see that the region outside the dielectric strip can be considered as a multilayerd dielectric waveguide sandwiched with two metal plates. Therefore the non-radiative condition for unbalanced insulated NRD waveguide is just the cut-off condition for modes guided by layered slab dielectric waveguide outside the dielectric strip line.

This kind of layered slab dielectric waveguide has been thoroughly studied in [5]. The modal cut-off feature is shown in Fig. 2. From this figure we can find that the non-radiative condition for the unbalanced insulated NRD-guide is almost the same as that for the standard NRD waveguide without considering the lowest mode TM_1, i.e.

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$$h/\lambda_0 < 0.5 \quad (1)$$

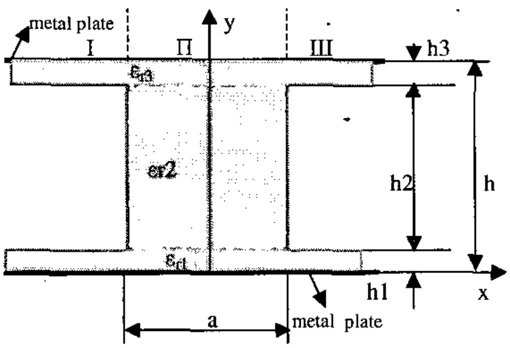

Fig.1 Cross section of unbalanced insulated NRD-guide.

B. *Condition for Leakage*

Wave propagation properties, including leakage, of the standard NRD guide has been extensively analyzed in [4] and the results illustrated that no leakage effects are present that could affect the behavior of NRD-guide components. When the dielectric strip line is sandwiched between substrates as shown in Fig. 1, the above conclusion obtained in [4] is no longer valid. Tang et al. have studied the leakage in this structure [3], but they failed to give the general condition related to leakage.

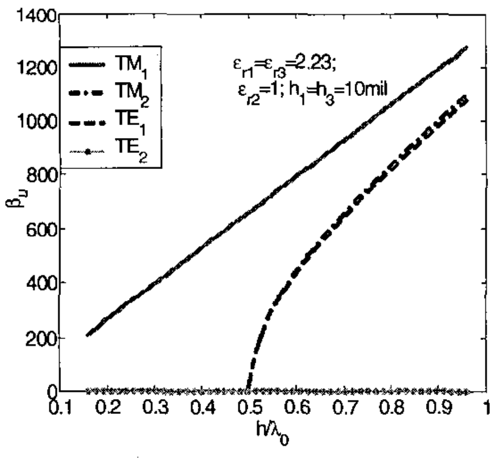

Fig. 2 Cutoff characteristics in layered slab guide (β_u is propagation constant).

For this unbalanced insulated NRD-guide, there are neither exact LSM nor LSE modes but hybrid types. The field distributions of modes are similar to those of the pure LSM or LSE modes. We call such modes in this dielectric waveguide quasi-LSM mode or quasi-LSE modes. The working mode is quasi-LSM_{01} mode.

Fig. 3 illustrates modal dispersion curve versus frequency. The working mode can be considered as a consequence by scattering when the lowest TE mode in the core dielectric strip is incident at an angle on the side of the dielectric strip. Because of TE-TM coupling at the dielectric interface, all kinds of TE and TM modes will be excited in the slab region III and I (see Fig. 1). The lowest mode in the slab waveguide is TM_1 mode. Since higher-order TM and TE modes are under cut-off condition (see Fig. 2), the mode that may carry energy away from the dielectric core strip and therefore result in leakage, may only be TM_1 mode in the layered slab waveguide. Suppose that β_u is the propagation constant of this TM mode, and β_z is for quasi-LSM_{01} mode. Then the condition for leakage is

$$\beta_z/\beta_u < 1 \quad (2)$$

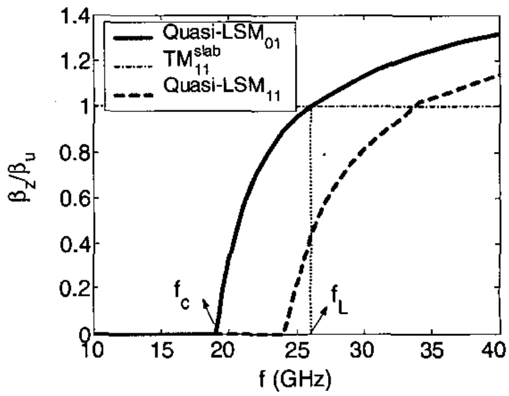

Fig. 3 Propagation characteristics of unbalanced insulated NRD-guide.

Equation (2) means that if we let $\beta_z > \beta_u$, we can suppress the leakage. It should be noted that the above condition is a general rule for leakage and this condition is different from that for the leakage cancellation: $(k_x^{TM}a)_{in}=2\pi$, under which the leakage is cancelled because of the resonance effects as discussed in [3]. For the purpose of practical design, we should adequately choose the geometrical parameters of waveguide to dissatisfy the condition set by (2).

From Fig. 3 we can find that as frequency increases, the mode propagation presents three distinct regions: "classical" cutoff phase, leakage, and bounded states. This is quite different from that in the standard NRD waveguide. When f is less than f_C, the mode is cutoff, and while f is between f_C and f_L, the mode is leaky. Only when f is higher than f_L, the mode is bounded as in a standard NRD waveguide. We should call f_L the characteristic frequency at which $\beta_z/\beta_u=1$.

Fig.4 presents influence of dielectric constant of the core dielectric strip on f_L for the quasi-LSM_{01} mode. When only εr_2 increases, β_z will increase at the same frequency point, but β_u does not change. Therefore we can find that with εr_2 increasing, f_L shifts to lower frequency and therefore the bandwidth in the absence of leakage increases.

Fig.5 illustrates the dependence of f_L on width "a" of the core dielectric strip line. Suppose that the effective dielectric constant in core strip region II (see Fig. 1) is ε_{e1}, then $\beta_z=(\varepsilon_{e1}k_0^2-kx^2)^{1/2}$., in which kx is the wave number in x-direction in the core dielectric region. When "a" is changed while keeping other parameters constant, kx will vary with "a", but kx must satisfy the eigenvalue equation in x-direction. So β_z will be different at the same frequency with different "a". Meanwhile, β_u is constant, so f_L at which $\beta_z=\beta_u$ will vary with "a". There is an optimum width "a" at which we can get minimum f_L.

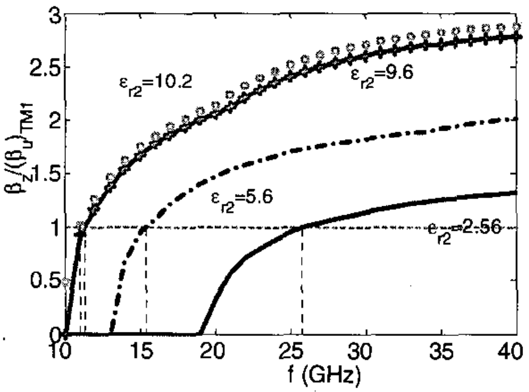

Fig. 4 Effect of dielectric constant εr_2 on f_L for quasi_LSM_{01} mode with h1=h3=10mil, h=4.8mm, a=4.3mm, and $\varepsilon r_1=\varepsilon r_3=2.23$.

Fig.6 displays the effect of asymmetry in y-direction on the characteristic frequency f_L. We use Δh=h3-h1 to express the degree of asymmetry. For symmetric substrates, Δh=0. We keep the space h between the two metal plates constant.

Suppose that the effective dielectric constant in region IIII and I is ε_{e2}. When Δh increases, ε_{e2} will increase and therefore β_u will increase at the same frequency. As we can find from Fig. 6 that with increasing Δh, the characteristics f_L shift towards to higher frequency and bandwidth without leakage will decrease.

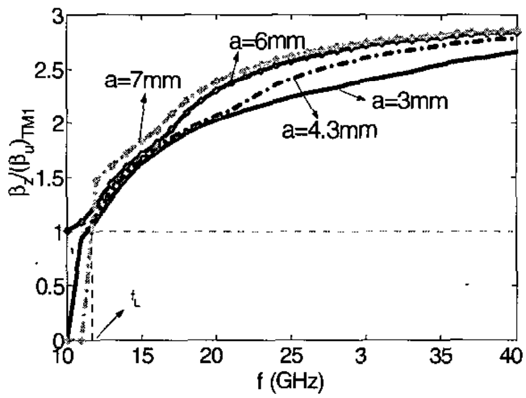

Fig. 5 Effect of width "a" of the core dielectric strip line on f_L of quasi_LSM_{01} mode with h1=h3=10mil, h=4.8mm, $\varepsilon r_1=\varepsilon r_3=2.23$, and $\varepsilon r_2=9.6$

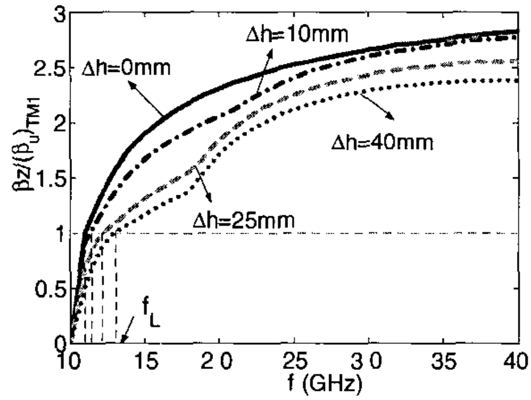

Fig. 6 Effect of asymmetry degree Δh=(h3-h1) on f_L for quasi_LSM_{01} mode with h1= 10mil, h=4.8mm, a=4.3mm, and $\varepsilon r_1=\varepsilon r_3=2.23$, $\varepsilon r_2=9.6$.

C. Single Mode Bandwidth Without Leakage

It is quite different from the standard NRD waveguide where the operating mode is not leaky. For the operating mode in unbalanced insulated NRD waveguide, leakage may be well present, as we have discussed in the above section. Therefore, as far as the monomode conditions are concerned, we must look into the conditions in the absence of leakage. For the single mode operation without leakage, the following requirements must be satisfied

$$\begin{cases} \lambda_0/2, \lambda_{g0}/2 > h > \lambda_{g1}/2 \\ \beta_z/\beta_u > 1 \end{cases} \quad (3)$$

in which λg_0, λg_1 are the guided wavelengths of quasi-LSM_{01} and quasi-LSM_{11} modes.

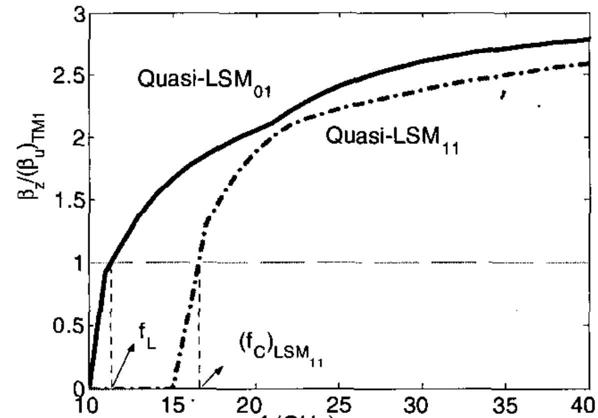

Fig. 7 Frequency range of single mode operation without leakage with parameters h1=h3=10mil, h=4.8mm, a=4.3mm, and $\varepsilon r_1 = \varepsilon r_3 = 2.23$, $\varepsilon r_2 = 9.6$

Fig. 7 shows the frequency range with the single mode operation. From this figure we can see that the single mode bandwidth without leakage is $B=(f_C)_{LSM11}-f_L$. Because of the leakage, the bandwidth is smaller than that in the standard NRD-guide, where the bandwidth is just $(f_C)_{LSM11}$- $(f_C)_{LSM01}$. In the case of $(f_C)_{LSM11}<(f_L)_{LSM01}$, there will not exist a single mode operation frequency range without leakage.

Fig. 3 shows this scenario, where the cutoff frequency of LSM_{11}mode is less than the characteristic frequency f_L of the quasi-LSM_{01} mode. To increase the bandwidth B, we should try to decrease the characteristic frequency f_L to $(f_C)_{LSM01}$. From Fig.4 we know that we can get a smaller f_L by using the core dielectric strip line with higher permittivity.

III. Conclusion

We have presented general properties of wave guidance and leakage of the insulated NRD-guide. We can conclude that the unbalanced insulated NRD-guide preserves most properties of the standard NRD-guide under certain conditions. The effect of leakage will reduce the effective bandwidth of single mode operation. This guided-wave structure can be applied in the design platform for low-loss and low-cost co-layered hybrid integrated microwave and millimeter wave circuits.

References

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