SURFACE-WAVE ELIMINATION IN INTEGRATED CIRCUIT STRUCTURES WITH ARTIFICIAL PERIODIC MATERIALS

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Abstract

Surface-wave (or dielectric slab) modes in integrated circuit structures often result in undesired energy losses and cross talk between components. In this paper, we investigate the feasibility of surface-wave elimination in integrated circuit structures by using planar artificial periodic (photonic band-gap) substrates. A full-wave 3-D integral-equation moment-method is employed to find the propagation constants of guided-wave modes on grounded dielectric slabs with planar periodic implants. Rectangular blocks in both a rectangular lattice and a triangular lattice are investigated. It is found that surface-waves forbidden characteristics are mostly determined by the lattice structures and insensitive to the shape and size of the periodic elements. Attempt has been made to obtain the omnidirectional wave band-gap. The limitation on complete surface-wave elimination is discussed. This paper initiates the investigation of a class of novel integrated circuit components which have potential applications in millimeter-waves and optics.

I. Introduction

In recent years, photonic band-gap (PBG) materials have drawn significant attention in the physics and engineering communities for their analogy to semiconductor crystals with electron band gaps [1-2]. These materials are basically an artificial structure made of periodic elements within a surrounding medium, which is usually free space or a low-loss dielectric medium. Electromagnetic wave propagation both internal and external to such a material is affected by the scattering and diffraction properties of the periodic elements. When the periodic elements are electrically large enough, there may exist frequency bands, (i.e. photonic bands), over which wave propagation is prohibited in certain or all directions.

Printed circuit elements placed on a semiconductor substrate are known to generate surface-wave modes (or dielectric slab modes). There are two major effects of the surface-wave mode generation. Surface waves which propagate laterally, are distinct from space waves and are considered losses in integrated circuits. Cross talk between devices printed monolithically on the surface of the substrate is mostly due to the surface wave propagation. It is often desirable to eliminate or minimize the surface wave generation. A solution is to use the artificial periodic material as the substrate for printed antennas. It is known in integrated optics that propagating (photonic) band gaps exist for guided waves in corrugated dielectric slabs [3]. The idea is that if we can tailor the surface-wave characteristics by machining the substrate into a planar periodic medium, the surface wave may be eliminated in partial or all directions within the frequency band-gap zone. To facilitate this investigation, recently we developed a three-dimensional full-wave integral-equation moment-method analysis of the surface-wave characteristics for layered structures with planar periodic blocks [4-5]. The aim of this paper is through this accurate numerical approach to study the surface-wave band diagram for a class of artificial periodic material substrates. The idea is to have a systematic scheme to predict the surface-wave characteristics. As examples, we

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present in this paper the cases of artificial periodic material with air implants of rectangular cylinders in a rectangular or triangular lattice.

II. Method of analysis

The full-wave analysis is for a grounded dielectric slab with planar material gratings shown in Figures 1 and 2 for a rectangular and a triangular lattice, respectively. The geometry is assumed infinite planar arrays of material blocks within a surrounding layer. The top region is air and the bottom region is a conductor ground. Although the implants shown in Figure 1 and 2 are for rectangular cylinders, the analysis also holds for most other irregular implants. The electric-field integral equation for the pertinent problem is formulated in terms of displacement current $\vec{J}_e$ that exists only within the implants. The pertinent structure is periodic and Floquet's theorem can be applied to simplify the problem to the modeling of electromagnetic waves within a semi-infinitely long cylinder. A finite-element moment-method procedure is applied numerically to determine the electric fields within the material implants. This is done by discretizing the material implants into many small cells within which the fields are assumed constants, but with unknown coefficients. The moment method converts the integral equations into a set of linear equations (a matrix equation. Nontrivial solution for the fields requires the matrix determinant to be zero, which results a characteristic equation. The eigenvalues (propagation constants) β are obtained from the roots of this equation for a given direction. For a lossless structure, the propagation constant of a guided (surface) wave is a real number, and a bisection method for finding the roots of nonlinear functions is used. Extensive validity check of the present analysis has been performed [4-5]. It has been observed that for higher the frequencies or larger sizes, more expansion cells are needed to obtained reasonable convergence. The number of cells in the vertical (z) direction is more crucial. Generally, vertical-cell size about a tenth of wave length provides reasonable convergence.

III. Results and Discussions

The molding of surface-wave modes of a grounded substrate with planar material gratings is of potential significance in integrated circuit applications. An important question to answer is "can we design a planar grating structure such that surface-wave can be eliminated in all directions". If not, then what is the limitation and how do we design the materials so that surface-wave elimination occurs in desired directions. An aim of this paper is to provide a fundamental understanding of the surface-wave band characteristics.

An example of dispersion diagram for guided and leaky wave modes of a grounded dielectric slab with 2-D rectangular material gratings (Figure 1) is shown in Figure 2 for propagation in the $\hat{x}$ direction. For the $\hat{x}$-direction waves, the mode characteristics are similar to the case for 1-D grating. There exist surface-wave band gaps for modes near the Brillouin zone boundary $\beta\ a = \pi$. At low frequencies, the fundamental modes are similar to a TM mode of a grounded dielectric slab. When the frequencies are such that Bragg condition is satisfied, the bounded modes turn to complex-wave modes (band gap zone). Strictly speaking, the wave within the band-gap zone is also a leaky-wave (slow-wave however) with a large attenuation constant. As frequency increases further beyond the band-gap zone, bounded surface-wave modes (in slow wave zone) turn into proper leaky wave modes (in the fast wave zone). The leaky-wave (fast-wave) modes which are of great interest for antenna application are discussed elsewhere [5].

It is seen from Figure 3 that within the band-gap zone there is no wave propagation. The results in Figure 3 are only for wave in the $\hat{x}$ direction. The results of the surface-wave band-gap versus directions are shown in Figure 4. The dashed line is the lower end and the solid line is the higher end of the surface-wave bad-gap. Due to the symmetry, the irreducible Brillouin zone is for θ

angle from 0 to 45 degrees (the mode diagram repeated every 45 degrees). It has been shown in [6] that there exist propagation band-gaps in one-dimensional material grating structures. It has also been shown in [7] that complete band gap exists in planar material grating within a dielectric layer sandwiched by conductor plates (2-D structures). The example given in Figures 3 and 4 shows that there is no frequency zone where surface-wave mode is completely eliminated. This phenomenon can be explained by recognizing that the Bragg diffraction condition for surface-wave in arbitrary direction is $\beta\, a \cos\theta \approx \pi$. Therefore, as θ increases from 0 (the x axis), the band-gap occurs at larger β, the phase constant. Since the phase constant increases with frequency, the band-gap occurs at higher frequencies for larger θ (but still less than 45 degrees). Therefore, unless the band-gap is wide and the substrate material is anisotropic, full mode elimination is not possible at a given frequency in all directions.

Another example we investigated is for blocks (cylinders) in a triangular periodic lattice on a grounded dielectric substrate. The results of the mode diagram for wave in the $\hat{x}$ direction is shown in Figure 5. For blocks in a triangular lattice, surface-wave band-gap is not found in any direction. The explanation is that for any given direction although the structure is periodic, the equi-phase plane is not a uniform structure and the Bragg condition can not apply. The general observation of surface-wave elimination is that the shape of the periodic element is not critical. The band-gap characteristics are determined mostly by the shape and size of the periodic lattice.

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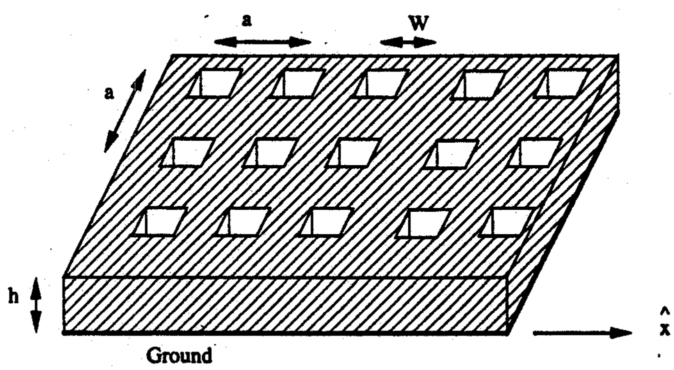

Figure 1. Square blocks within a square lattice on a grounded dielectric substrate.

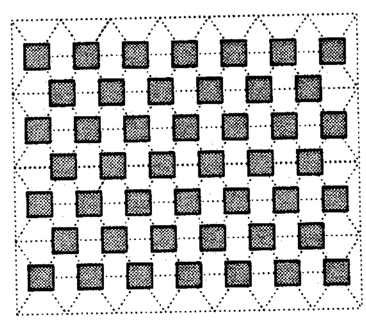

Figure 2. Top View of Rectangular Blocks Within a Triangular Periodic Lattice on a Grounded Dielectric Substrate.

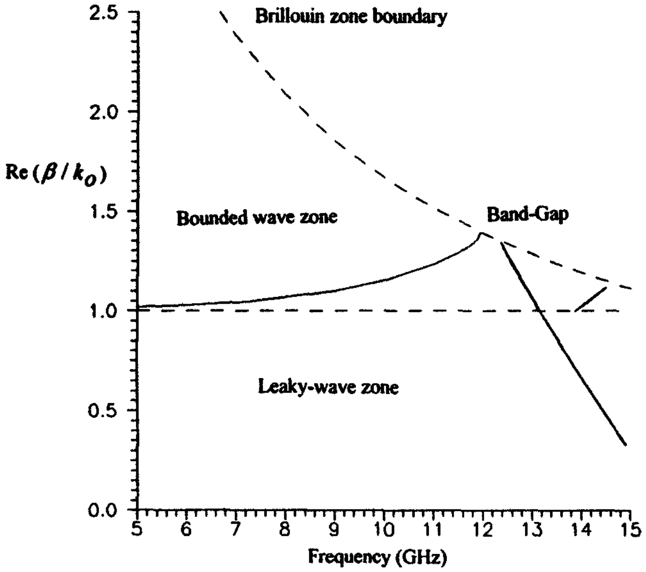

Figure 3. Dispersion diagram for modes in a grounded slab with planar rectangular air blocks (Figure 1). h = 2 mm, w = 5 mm, a = 9 mm, block depth 1.0 mm, ε = 10, and the propagation is in the $\hat{x}$ direction.

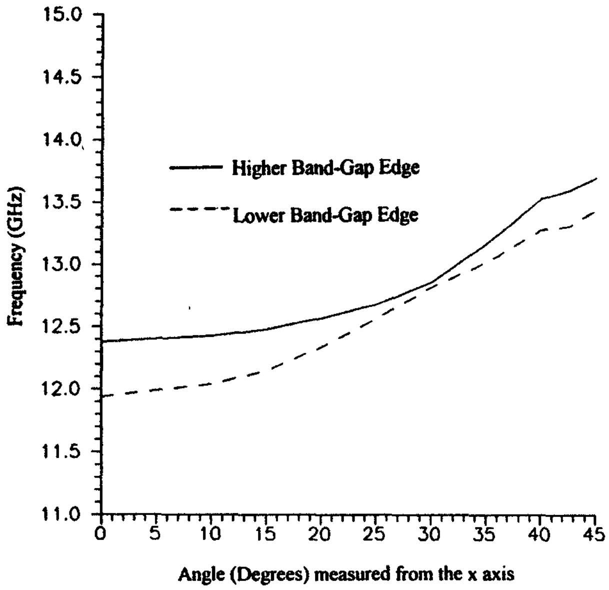

Figure 4. Surface-wave band-gap versus propagation angle for the case shown in Figs. 1 and 3.

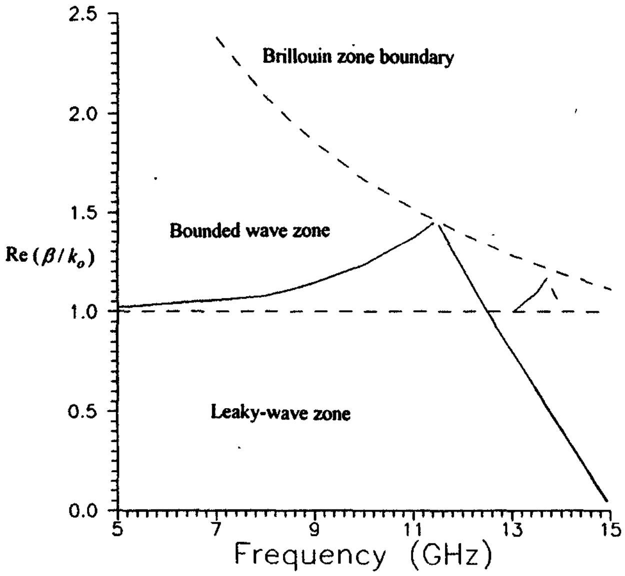

Figure 5. Dispersion diagram for modes in a grounded slab with air blocks within a triangular lattice (Figure 2). h = 2 mm, w = 5 mm, a = 9 mm, block depth 1.0 mm, ε = 10, and the propagation is in the $\hat{x}$ direction.

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