DESIGN OF PHOTONIC BAND-GAP SUBSTRATES FOR SURFACE WAVES SUPPRESSION

Roberto Coccioli and Tatsuo Itoh
Electrical Engineering Department, University of California, Los Angeles, CA 90095-1594, U.S.A.

ABSTRACT. Suppression of unwanted surface waves supported by grounded dielectric slab can be achieved by periodically loading the substrates to create forbidden frequency band for propagation. Approximate formulas for designing such loading are given and verified by means of a numerical full-wave analysis.

Introduction.

Surface wave propagation in dielectric substrates often negatively affects the performances of microwave and millimeter wave circuits. For instance, it may reduce the efficiency of planar antennas on high dielectric constant substrates or may produce unwanted coupling between different parts of circuits. It is difficult to evaluate this latter effect in the design stage since it can be accurately assessed only using computational intensive full-wave numerical techniques to analyze the whole circuit. Consequently, its presence may slow down the tuning and troubleshooting phase of circuit development.

Suppression of unwanted surface waves and control of their propagation is desirable not only to improve circuits performances. It can also lead to realization of new devices and low-loss guiding structures, particularly useful at millimeter wave frequencies where metallic losses in microstrips or coplanar waveguide become significant.

The usage of geometric periodicity to create a band-gap in the dispersion diagram of surface waves, forbidding propagation in grounded dielectric slabs for specific directions and ranges of frequency is shown in this work. Periodicity is along two directions, not necessarily perpendicular and can be introduced in different ways. The idea of exploiting the forbidden band-gap created by periodicity has recently had a new boost due to the exciting applications at optical frequencies [1,2], and a renewed interest is arising for its application at microwave and millimeter wave frequency as well. Some possible applications have already been investigated [3-5].

The geometry investigated.

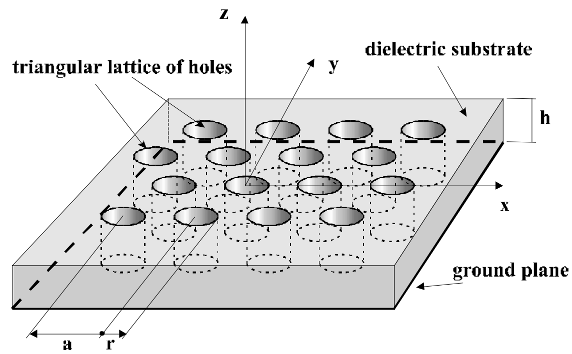
Two different kinds of periodically loaded, grounded dielectric slabs have been investigated. The first kind is realized by drilling holes in the dielectric, while in the second holes are etched in the ground plane. Both kinds of loading may be arranged in a square or triangular lattice. In general, determining the dispersion diagram of a guiding structure is a heavy computational task. Computational time is further increased in this case by the fact that many directions of propagation of the waves need to be considered. As a matter of fact, a complete characterization of the periodically loaded substrate requires performing a full-wave analysis along the edges of the Brillouin zone in the reciprocal space. Although this cannot be avoided to get accurate results, approximate analytical formulas can be derived to estimate the lattice constant of the periodic loading that gives the desired center frequency of the first forbidden band-gap for the two different type of loading.

0-7803-4471-5/98/$10.00 (c) 1998 IEEE

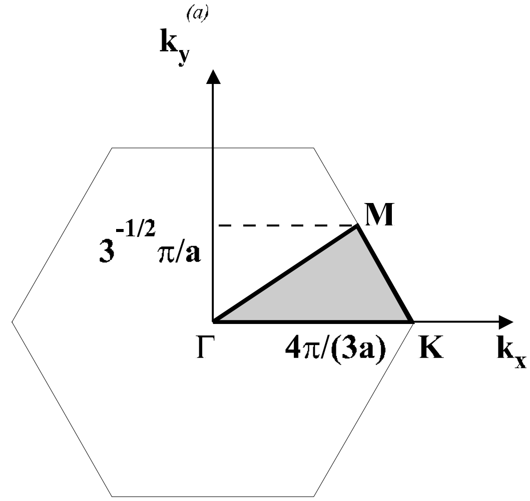
A. Holes in the dielectric substrate.

Usually, the values of dielectric constant and thickness of grounded slabs used as substrates for microwave and millimeter waves circuits is such that only the fundamental TM_0 surface wave mode can propagate in the substrates when excited by discontinuities, or by planar antennas. Then, this is the mode that the designer may want to be able to forbid, without allowing propagation for the other modes at the same time. Let us assume that f_0 is the center frequency of the desired stop-band for the TM_0 mode, and let us select a triangular lattice to load the substrate (Fig. 1*a*). The triangular lattice is chosen because it has proved capable, in the simpler case of a two-dimensional photonic crystal, of providing a stop-band for any in-plane (β_z=0) direction of propagation due to the high symmetry of the Brillouin Zone (BZ) associated to it [6]. This latter is the hexagon shown in Fig. 1*b*. As well known from periodic structure theory, a band-gap in the dispersion curves will show up at the edges of the BZ. In particular, we can focus our attention on the two directions of propagation corresponding to the edges ΓK and ΓM of the Brillouin Zone. The gaps should appear at the vertexes M and K. Frequency values corresponding to a propagation vector β at points M or K are generally unknown for the actual periodic structure. However, in the case of small perturbations, i.e. for small values of the *r/a* ratio, they can be estimated using the propagation constant in the unperturbed structure. For higher values of the *r/a* ratio, they can be estimated by resorting to the concept of effective dielectric constant ε_{eff} of the perforated substrate. Using the quasi-static volumetric principle for the case of triangular lattice:

$$\varepsilon_{eff} = \varepsilon_r \left(1 - \frac{2\pi}{\sqrt{3}} \frac{r^2}{a^2}\right) \qquad (1)$$



(a)



(b)

Fig. 1 – *a)* Triangular lattice of holes in a grounded dielectric slab. The ground plane is not pierced; *b)* Irreducible Brillouin zone (shaded region) in the k vector space

Apparently, the higher the radius of the hole, the lower the effective dielectric constant of the substrate. Using this value of the effective dielectric constant, its easy to compute the propagation constant $\beta(f_0)$ of the fundamental TM_0 surface wave at the frequency f_0 at which the stop band should be centered. At this point, the values of the lattice constant *a* providing a stop-band centered around f_0 for propagation along the directions ΓK and ΓM are given, respectively, by:

$$a = \frac{4\pi}{3\beta(f_0)} \qquad \text{along } \Gamma\text{K} \qquad (2)$$

$$a = \frac{2\pi}{\sqrt{3}\beta(f_0)} \qquad \text{along } \Gamma\text{M} \qquad (3)$$

It is seen that there is a 13.4% difference between the values provided by equations (2) and (3). If the propagation of surface waves must be forbidden in one direction only, then this is not a problem since one can choose the appropriate value of *a* using the above formula. If a total stop-band must be achieved, that is propagation must be forbidden in any directions, then the lattice constant *a* may be chosen at an intermediate value between the two above. This does not guarantee the presence of a forbidden band-gap along any direction of propagation, since this will be achieved only if the width of the band-gap at the two points K and M is wide enough to overlap.

Assessing the width of the band-gap is a more difficult task. However, the general trend is that the stronger the perturbation, the wider the band-gap. Thus, high values of the ratio are needed to realize substrates featuring a complete stop-band.

B. Holes etched in the ground plane.

The design of this second kind of periodic loading follows the same path as in the previous case. The only difference is that now, since the dielectric substrate is not drilled, there is no need to introduce an effective dielectric constant. The value of the propagation constant $\beta(f_0)$ of the fundamental TM_0 surface wave at the design frequency f_0 can be computed using the actual value of dielectric constant of the substrates. Then, the lattice constant *a* can be again evaluated employing the same equations used in the case of a perforated substrates.

Results.

The simple formulas (2) and (3), have been used to design a substrate that presents a stop band along the direction of propagation ΓM (θ=0, ϕ=π/6). The design frequency has been chosen 8.8GHz. The dielectric constant of the substrate is 10.2 and its thickness is 200mil. The value of the *r/a* ratio is chosen equal to 0.25, and the lattice is triangular. For such value of *r/a*, the effective dielectric constant of the substrate is equal to 7.9. The propagation constant at 8.8GHz for a homogeneous dielectric substrate with thickness 200mil is computed using the well known formulas [7] and is 413m^{-1}. The constant lattice *a* to have a stop band centered at 8.8 GHz along the ΓM direction is then estimated using the simple formulas above as equal to 8.8mm. Using these values for the substrate geometry, a full wave analysis has been performed using FDTD. The dispersion diagram for surface waves along the ΓM direction is shown in Fig. 2. It is seen the presence of a forbidden band-gap in the frequency range 8.7-9.7GHz. The estimated center frequency differs of about 5.5% from the computed one. The simple equations (1)-(3), even though not highly accurate, constitute a good starting point for the design procedure and may avoid many computationally intensive cycles before arriving at the desired value of the band-gap center frequency.

References

[1] E. Yablonovitch, “Inhibited spontaneous emission in solid-state physics and electronics,” *Physical Rewiev Letters*, vol. 58, no. 20, pp. 2059-2062, May 1987.

[2] M. Boroditsky, R. Coccioli, E. Yablonovitch, "Analysis of photonic

crystals for light-emitting diodes using the finite difference time domain technique", *Proceedings of Photonics West '98*, pp. 3283-38, San Jose, CA, Jan 20-24, 1998.

[3] T.J. Ellis, G.M. Rebeiz, "MM-wave tapered slot antennas on micrimachined photonic bandgap dielectrics," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1157-1160, June 1996.

[4] V. Radisic, Y. Qian, T. Itoh, "Broadband amplifier using dielectric photonic band-gap structure," *IEEE Microwave Guided Wave Lett.*, in print.

[5] V. Radisic, Y. Qian, R. Coccioli, T. Itoh, "A novel 2-D photonic band-gap structure for microstrip lines," *IEEE Microwave Guided Wave Lett.*, vol. 8 no. 2, Feb. 1998

[6] J.D. Joannopoulos, R.D. Meade, J.N. Winn. *Photonic Crystal. Molding the flow of light*. Princeton University Press, Princeton, NJ, 1995.

[7] D.M. Pozar. *Microwave Engineering*. Addison Wiley, Reading, MS, 1990.