ACKNOWLEDGMENT

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REFERENCES

1. R.C. Liu, K.L. Deng, and H. Wang, A 0.6–22-GHz broadband CMOS distribted amplifier, Proc IEEE RFIC Symp, Philadelphia, PA (2003), 104–106.
2. R.C. Liu, K.L. Deng, and H. Wang, A 0.5–14-GHz 10.6dB CMOS cascode distribted amplifier, Proc. IEEE VLSI Circuits Symp (2003), 139–140.
3. M.-D. Tsai, K.-L. Deng, H. Wang, C.-H. Chen, C.-S. Chang, and J.G. Chern, A miniature 25-GHz 9-dB CMOS cascaded single-stage distributed amplifier, IEEE Microwave Wireless Compon Lett 14 (2004), 554–556.
4. R.E. Amaya, N.G. Tarr, C. Plett, A 27 GHz fully integrated CMOS distributed amplifier using coplanar waveguide, Proc. IEEE RFIC Symp, Fort Worth, TX (2004) 193–196.
5. S. Galal and B. Razavi, 40-Gb/s amplifier and ESD protection circuit in 0.18-μm CMOS technology, IEEE J Solid State Circuits (2004), 2389–2396.
6. T.-Y. Chen, J.-C. Chien, and L.-H. Lu, A 45.6-GHz matrix distributed amplifier in 0.18-μm CMOS, Proc IEEE Custom Integrated Circuits Conf (2005), 119–122.
7. K. Kobayashi, R. Esfandiari, M. Hafize, D. Streit, A. Oki, L. Tran, and M. Kim, GaAs HBT wideband matrix distributed and darlington feedback amplifier to 24 GHz, IEEE Trans Microwave Theory Tech 39 (1991).
8. K.W. Chang, B.L. Nelson, A.K. Oki, D.K. Umemoto, 2–19-GHz low-DC power and high-IP$_3$ monolithic HBT matrix amplifier, IEEE Microwave Guided Wave Lett 2 (1992), 2001–2009.
9. K. Kobayashi, R. Esfandiari, W. Jones, K. Minot, B. Allen, A. Freudenthal, and D. Streit, A 6–21-GHz monolithic HEMT 2 $\times$3 matrix distributed amplifier amplifier, IEEE Microwave Guided Wave Lett 3 (1993) .
10. T.H. Lee, The Design of CMOS Radio-Frequency Integrated Circuits, Cambridge University Press, Cambridge, 1998.

OMNIDIRECTIONAL STOP BAND BY USING COMPOSITE TWO-DIMENSIONALLY ARTIFICIAL CRYSTAL

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ABSTRACT: *We present here a study of the wave propagation in a two-dimensionally (2D) periodic structure. The scattering of a plane wave by a 2D periodic structure is analyzed as a multilayer boundary-value problem. Specific examples are given to show quantitatively the stopband behaviors; in particular, a composite structure with different lattice patterns in cascade is shown to achieve the broad and omnidirection behavior of stop band.* © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 1914–1917, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22569

Key words: *photonic crystals; periodic structures; stop band*

1. INTRODUCTION

The development of artificial materials by constructing lattice structure has gained considerable attention in recent years; in particular, the stop band phenomenon associated with the lattice structures has found many applications. For example, an antenna substrate etched with 2D periodic holes has been utilized to suppress the surface waves introduced by printed antenna [1]. The 2D periodic layers in conjunction with planar structures have been investigated for both optical and microwave applications; one example is a high impedance surface that will not support a surface wave in any direction [2]. A 2D periodic array of dielectric rods in a uniform surrounding has been shown to exhibit many interesting phenomena, such as spontaneous emission and localization of electromagnetic energy. Such periodic arrays of dielectric materials were employed as a novel waveguide to mold the flow of electromagnetic energy [3] or as a novel cavity to store energy. The basic concept of this class of applications can be traced back to the early work of Larsen and Oliner [4] who had used one-dimensional (1D) periodic slabs to form waveguide walls that are operated in their stop band or below cutoff condition.

The structure under study is a 2D periodic rectangular dielectric rods array immersed in a uniform surrounding, such as air. Where the 2D periodic array is composed of N one dimensionally periodic layers of infinite horizontal plane, which is stacked with equal spacing between two neighboring ones. Each periodic layer is composed of an infinite number of rectangular dielectric rods of infinite length. In addition, we can have by displacing every second row by a fractional part of the period to form any 2D lattice pattern.

As to the numerical analysis of the periodic structures, many authors have employed diverse method to analyze such problem, for example, the finite-difference method and finite-difference time-domain (FDTD) method have utilized to calculate the fields and the dispersion curves of guide mode [5]. For the scattering of the stack of 1D periodic layer, Peng has employed rigorous mode matching method and cascade of transmission-line network method to deal with the 1D grating with irregular shape [6]. In this research, since 2D periodic structure could be considered as cascade of 1D periodic layers and uniform layers, we can employ the same method to carry out the calculations. The Floquet-type solutions are constructed with the results shown in the form of dispersions for an unbound media, while the scattering of plane wave by 2D periodic structure of finite thickness is analyzed as a multilayer boundary-value problem to verify the dispersion characteristics.

The purpose of this article is to provide a theoretical basis for the analysis of 2D periodic structure, so that the benchmark results can be established for verifying those obtained from experiments, or obtained by simple, approximate analysis. Specific examples are given to show quantitatively the stop band behaviors; in particular, a composite structure with difference lattice pattern in cascade is shown to achieve the broad and omnidirectional behavior of stop band.

Figure 1 shows a stack of N identical periodic layers of infinite extent on the horizontal plane, which are stacked with equal spacing between two neighboring ones. Each periodic layer is composed of an infinite number of rectangular dielectric rods of infinite length. When the number of the periodic layers in the stack is increased indefinitely, the structure can be viewed as an unbounded 2D periodic media. Therefore, we may infer the propagation characteristics of the 2D periodic medium by the scattering characteristics of a stack of sufficiently large number of 1D periodic layers. With the coordinate system attached, the dielectric

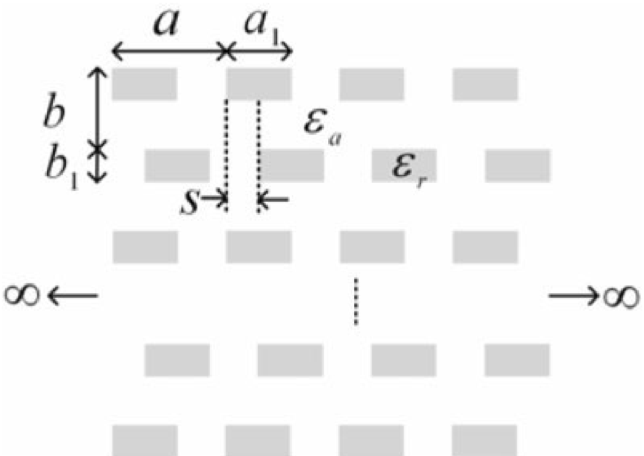

Figure 1 Geometric configuration of 2D periodic array

rods in each layer has the width a_1 and distance between two neighboring rods is a–a_1, so that the periodic of the layer is a. To simplify, a_1/a will be referred to as the aspect ratio of the 1D periodic layer. The thickness of the 1D periodic layer is b_1 and the separation between two neighboring ones is b–b_1. In general, we assume that between two neighboring layers, there is a position shift of the distance s in lateral direction, so that we may investigate the effect of a large class of array patterns on propagation characteristics of a 2D periodic medium by adjusting the parameter s in our analysis. For example, we have a square array pattern for $s = 0$ and a triangular pattern for $s = 0.5$. It is noted that for an arbitrary value of s, b is not necessarily the periodic in y-direction; actually, the structure has a period $(s^2 + b^2)^{1/2}$ along the direction at the angle $\theta = \sin-1$ (s/b) from the y-axis. Even through, the ratio b_1/b will be referred to as the aspect ratio in y-direction.

Referring to Figure 1, the 2D periodic structure consists of N 1D periodic layers and scattering of plane wave by such a structure can be easily analyzed as a rigorous multilayer boundary-value problem. The formulation of such a type of boundary-value problems can be carried out for any value of s and it is convenient for the analysis of the effect array pattern on the propagation characteristics of the 2D periodic medium. For simplicity, this will be referred to as the scattering approach.

As it will be explained in the following paragraphs, the scattering of plane-wave by a stack of 1D periodic layer may be analyzed in terms of that by a single 1D periodic layer. The scattering of plane-wave by a single 1D periodic layer has been well developed [6]. The formulation of the boundary-value problem is generally valid for any periodic profile, as long as the characteristic solutions of the periodic media can be constructed. For succinctness, the input–output relation for a 1D periodic layer is outlined below while the detail derivation can be consulted from the Ref. 6.The results are expressed in the form of input impedance and transfer matrices and will be used, as a building block, repeatedly for the analysis of plane-wave scattering by a stack of periodic layers, as will be done in the following paragraphs.

Dielectric function of infinite 2D periodic medic can be expanded using Fourier series as

$$\varepsilon(x,y) = \sum_p \sum_q \varepsilon_0 \varepsilon_{p,q} e^{-jp\frac{2\pi}{a}x} e^{-jq\frac{2\pi}{b}y} \tag{1}$$

where a and b are the period in x and y directions. Because of the spatial periodically in x and y, a set of Fourier components or space harmonic is generated everywhere in the structure; the propagation constant of the mth space harmonic in the x-direction and nth space harmonic in the y-direction are given by

$$k_{\mathrm{xm}} = k_{\mathrm{x}} + m\frac{2\pi}{a} \text{ for } m = \ldots, -2, -1, 0, 1, 2, \ldots \tag{2a}$$

$$k_{\mathrm{yn}} = k_y + n\frac{2\pi}{b} \text{ for } n = \ldots, -2, -1, 0, 1, 2, \ldots \tag{2b}$$

The general electric and magnetic field in the 2D periodic medium can be expressed as the super position of the complete set of space harmonics, each appearing as a plane wave, as given by

$$\psi(x,y,z) = \sum_{\mathrm{m}} \sum_{\mathrm{n}} \psi_{\mathrm{mn}} e^{-jk_{\mathrm{xm}}x} e^{-jk_{\mathrm{yn}}y} \tag{3}$$

Substituting (1) and (3) into Maxwell's equation leads to Helmotz wave equation. This equation is a standard eigenvalue problem. For each specific k, the frequency for the eigenmode is the eigenvalue of the equation. Using symmetry properties, we only calculate k–w relation in irreducible zone, and compare the results with the scattering characteristics. The scattering characteristics are calculated utilizing the method illustrated below.

For a 1D periodic layer, it is vertically uniform and characterized by relative dielectric constant

$$\varepsilon(x) = \varepsilon(x + a) \tag{4}$$

where a is the period. Because of the spatial periodically in x, a set of Fourier components or space harmonic is generated everywhere in the structure; the propagation constant of the mth space harmonic in the x-direction is given in (2a). Based on the Floque's theorem, the general field solutions can be expressed as a superposition of the complete set of space harmonics. The general electric and magnetic field solutions in 1D periodic medium can be written as [6]

$$\underline{E_t}(y) = Q[\exp(-jKy)\underline{c} + \exp(jKy)\underline{d}] \tag{6}$$

$$\underline{H_t}(y) = P[\exp(-jKy)\underline{c} - \exp(jKy)\underline{d}] \tag{7}$$

where the matrices P and Q are the coupling matrices and the element of them are dependent on the structural parameters as well the incident condition. K is the diagonal matrix with the propagation constant along y-direction, k_{yn}, as the nth diagonal elements.

By imposing the boundary condition at the interface between periodic and uniform layers, we could obtain the input–output relations of the periodic layer. The detail mathematical derivations can be found in Ref. 6 and we only list the result for reference.

$$\mathbf{Z}_{dn} = \mathbf{Q}(1 + \Gamma_l)(1 - \Gamma_l)^{-1}\mathbf{P}^{-1} \tag{8a}$$

$$\Gamma_l = \exp(-j\mathbf{K}t)\Gamma_{\mathrm{out}}\exp(-j\mathbf{K}t) \tag{8b}$$

$$\Gamma_{\mathrm{out}} = (\mathbf{Z}_{\mathrm{out}}\mathbf{P} + \mathbf{Q})(\mathbf{Z}_{\mathrm{out}}\mathbf{P} - \mathbf{Q})^{-1} \tag{8c}$$

$$\mathbf{T} = (\mathbf{Z}_{\mathrm{out}}\mathbf{P} + \mathbf{Q})(\mathbf{Z}_{\mathrm{out}}\mathbf{P} - \mathbf{Q})^{-1} \tag{8d}$$

where t is the thickness of 1D periodic layer, Z_{out} and Z_{in} are the output impedance matrices looking downward from the lower- and upper- surfaces of such 1D periodic layer, respectively. Whereas T is the transfer matrix, which defines the transformation relation of electric fields between the input and output interfaces. It is noted that the uniform layer can be considered as the limiting case of 1D periodic layer with vanishing of the periodic variations. In view of this, the input–output relation of uniform layer will remain almost the same form but with slight modification and could be consulted in the reference.

Underlying the output condition of the 2D periodic structures, we could successively employ the input–output relation of 1D periodic layer and uniform layer from the bottom- and top-layer. Thus we can obtain the input impedance matrix Z_{in} for looking downward from the top surface of the structure. The tangential electric and magnetic field vectors at the reference plane $y = 0$ are related by

$$E_t(0) = \mathbf{Z}_{in} H_t(0) \qquad (9)$$

On the other hand, the dielectric constant of a 2D periodic medium can be represented by a double Fourier series, and so are the electromagnetic fields, known as the Floquet type solutions. The Maxwell equations will then yield a set of homogenous linear equations that provides a rigorous basis for the analysis of wave propagation in the 2D periodic medium. The condition for existence of nontrivial solutions of the homogeneous linear equations leads to the vanishing of the coefficient matrix and this defines the dispersion relation of the medium. For simplify, this will be referred to as Floquet approach.

We have examined a number of 2D periodic structures with different structure parameters and different array patterns by both approaches, as illustrated below.

Figure 2 shows band structure of 2D periodic array with triangular lattice pattern and the aspect ratios: $a_1/a = 0.5$, $b_1/b = 0.5$. The relative dielectric constant of dielectric rods and surrounding media are 11.4 and 1.0. The first four complete stop bands are marked by A, B, C, and D. Throughout this work, all structures are illuminated by TE plane wave.

To investigate the refection of plane wave by a 2D periodic dielectric array, contours of constant reflection coefficient are plotted against the normalized frequency, a/λ and the incident angle. Figure 3 shows the contours of constant reflection coefficient for the case of 16 1D periodic layers with the same lattice pattern, aspect ratios and dielectric constant in Figure 2. The reflection coefficient is plotted in gray-scale color map according to the level specified by the color bar on the right side of the figure. The region drawn in white color represents that the reflection coefficient is very close to unity. As expected, there exist four stopbands, as also marked by A, B, C and D. Compare band structure with contours of constant reflection coefficient, and we can find that the stop bands agree with those of the infinite medium.

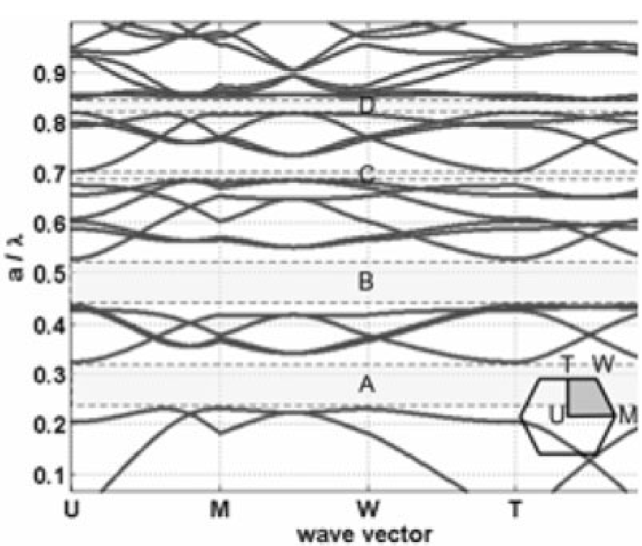

Figure 2 Dispersion relation for 2D periodic medium with dielectric constant 11.4 and the aspect ratio $a_1/a = 0.5$, $b_1/b = 0.5$, $a = b$

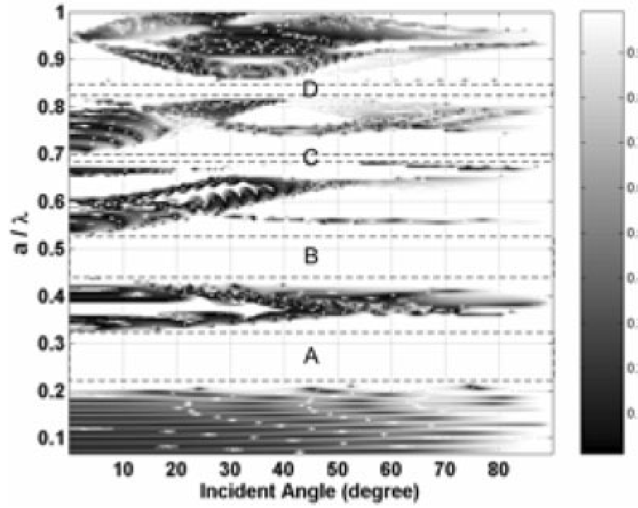

Figure 3 Contours of constant reflection coefficient for the 2D periodic structures with dielectric constant 11.4, 16 1D periodic layers and the aspect ratio $a_1/a = 0.5$, $b_1/b = 0.5$, $a = b$

In the following cases, the relative dielectric constant of the dielectric rods and surrounding media are 11.4 and 1.0. As shown in the Figure 3, the first structure yields the total reflection band in the normalized frequency range between 0.22 and 0.53, except for the normalized frequency between 0.32 and 0.41. By a proper choice of the parameters such as aspect ratios $a_1/a = 0.4$, $b_1/b = 0.2$ make the second one have total reflection between these two frequencies as shown in Figure 4. Thus, the stop band of two structures can compensate each other. As the Figure 5 indicates, the composite structure

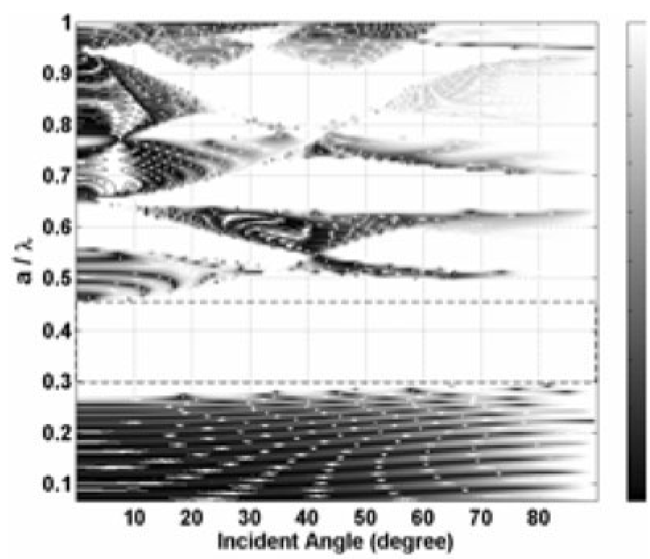

Figure 4 Contours of constant reflection coefficient for the 2D periodic structures with dielectric constant 11.4, 16 1D periodic layers and the aspect ratio $a_1/a = 0.4$, $b_1/b = 0.2$, $a = b$

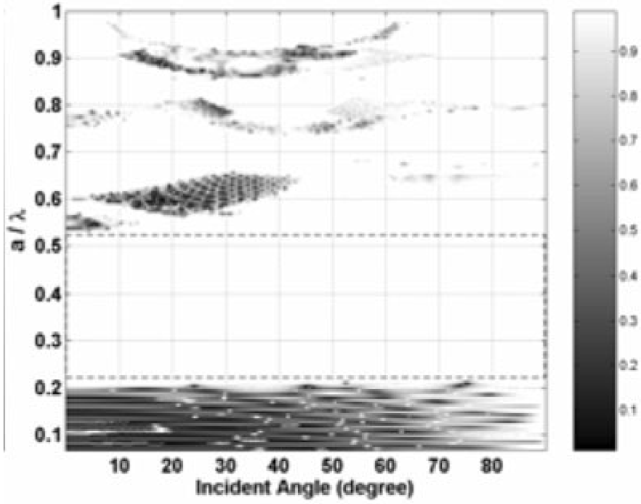

Figure 5 Contours of constant reflection coefficient for composite 2D periodic structure with 32 1D periodic layers

composed of above two structures exhibits perfectly omnidirectional total reflection band where the normalized frequency is between 0.22 and 0.53, and this band is the union of above two structures.

REFERENCES

1. H.-Y.D. Yang and J. Wang, Surface waves of printed antennas on planar artificial periodic dielectric structures, IEEE Trans Antennas Propag 49 (2001), 444.
2. R.F.J. Broas, D.F. Sievenpiper, and E. Yablonovitch, A high-impedance ground plane applied to a cell phone handset geometry, IEEE Trans Microwave Theory Tech 49 (2001), 1262.
3. A. Mekis, S. Fan, and J.D. Joannopoulos, Absorbing boundary conditions for FDTD simulations of photonic waveguides, IEEE Microwave Guidedwave Lett 9 (1999), 502.
4. R.P. Larsen and A.A. Oliner, A new class of low loss reactive wall waveguides, G-MTT Int Microwave Symp Program Dig (1967), 17.
5. A. Di Falco, C. Conti, and G. Assanto, Three-dimensional superprism effect in photonic-crystal slabs, J Lightwave Technol 22 (2004), 1748.
6. S.T. Peng, Rigorous formulation of scattering and guidance by dielectric wave guides: General case of oblique incidence, J Opt Soc Am A 6 (1989), 1869.

SIMPLE CAD FORMULAS OF SILICON BASED RFIC COMPONENTS BY SYNTHETIC ASYMPTOTE WITH INSIGHT AND FEW ARBITRARY CONSTANTS

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ABSTRACT: *This article derives simple computer-aided design (CAD) formulas of the components of Silicon, based radio frequency integrated circuits (Si-RFIC) by synthetic asymptote. The formulas include, those for microstripline, patch capacitor, and spiral inductor. With "boot-strapping", one can obtain, CAD formulas of the components from simple to more complicated and practical. These formulas are, simple, accurate, with good physical insights, and few arbitrary constants. Compared with numerical, methods, the average errors are less than 2%.* © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 1917–1921, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22568

Key words: *synthetic asymptote; CAD; RFIC*

1. INTRODUCTION

Radio Frequency Integrated Circuits (RFIC) are widely used in wireless communication, remote, sensing, navigation, etc. The modeling of practical components and circuits of RFIC becomes more, and more important. The main methods for the analysis and design of RFIC components and circuits, are based on electromagnetic (EM) formulation, such as: moment method (MoM) [1], finite element, method (FEM) [2], finite-difference time-domain (FDTD) [3], etc. Refer to these numerical methods, many commercial softwares are developed and widely used for full-wave analyses of RFIC, components and circuits.

As a novel modeling technique, synthetic asymptote has been used for obtaining simple CAD, formulas in recent years, such as the series papers [4-10]. Simply, the synthetic asymptote is, constructed from regular asymptotes (exact or nearly exact) at the two limits of a parameter. With one, or two intermediate match points from numerical solution, the maximum error say, 10%, in the, middle of the parameter range can be reduced to 3% or less. The formulas derived by synthetic, asymptote technique are simple, accurate, and give good physical insight.

The formulas in [4-10] are obtained for lossless substrate of one layer. For two layer lossless, grounded substrates, we also derived simple CAD formulas of patch capacitor, microstrip line, and square spiral inductor [11-13].

As an extension of our previous work, this article considers more practical components of silicon based RFIC (Si-RFIC). In practical design of Si-RFIC, the lossy substrate silicon (Si) may affect the performance of the components and then total circuits. By synthetic asymptote and bootstrapping, the CAD formulas of microstrip line, patch capacitor, and square inductor of Si-RFIC are obtained in this article. Compared with numerical results, the average errors are less than 2%.

2. CAD FORMULA OF MICROSTRIP LINE OF SI-RFIC

The formula for a microstrip line of Si-RFIC has been obtained in [14]. In this article, however, we only give a brief description of the formula. And in the following two sections, the formulas for patch capacitor and spiral inductors are derived by the same technique used in this section.

Figure 1 shows the structure of a microstrip line of Si-RFIC with the width W. The top layer is SiO_2 and the bottom layer is Si.

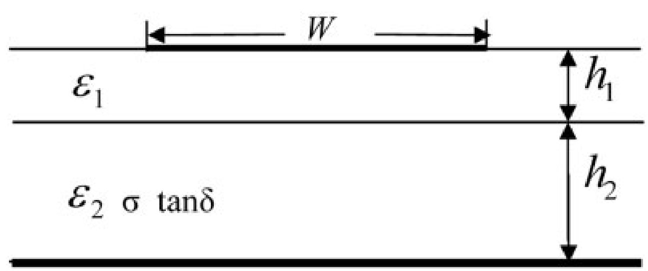

Figure 1 A microstrip line on grounded lossy substrate of two layers