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Analysis of the Reflection Characteristics of a Planar EBG Structure on Lossy Silicon Substrates

Qiang Liu, Yingzhe Xi, A.C.F. Reniers, A. B. Smolders, *Senior member IEEE*
Electromagnetic Group, Eindhoven University of Technology (TU/e)
P.O Box 513,5600MB Eindhoven, the Netherlands
Email: q.liu@tue.nl

***Abstract*—Electromagnetic band gap (EBG) structures can exhibit high impedance surface (HIS) performance on a lossless substrate. However, the performance of an EBG structure is not only determined by the type of element or physical dimensions, but also by the electrical characteristics of the dielectric substrate. The evolution of an EBG structure from HIS to metamaterial absorber with different lossy silicon substrates is analyzed and presented in a reflection magnitude and phase graph. The conductivity of the used substrate is introduced to represent the loss tangent of the silicon substrate. An equivalent circuit model is developed that models the EBG on a lossy silicon substrate. The small differences between calculated and simulated results are explained by ignoring the patch series inductance L_s and the capacitance C_h between the patch and ground plane. Based on the analysis of the reflection characteristics on lossy silicon substrates, this planar EBG structure provides an acceptable performance in BiCMOS technologies, but cannot be used in low-Ohmic CMOS technologies.**

***Index Terms*—Lossy substrate, Electromagnetic band-gap, high impedance surface.**

I. Introduction

Electromagnetic band gap (EBG) structures have received much attention over the past years. They are used for improving the high impedance surface (HIS) performance on lossless dielectric substrates. It can be used to reduce the mutual coupling between elements in array antennas [1], impedance matching for low profile wire antennas [2], achieve a high gain for a Fabry-Perot resonator antenna [3], and improve the radiation efficiency of an Antenna-on-Chip (AoC) [4].

The reflection properties of EBG structures can be analyzed by transmission line theory, and the model can be equivalent to a lumped element parallel LC circuit. Different EBG shapes like, for instance, a square patch, a square loop, and the Jerusalem cross, have been investigated using a relative simple equivalent-circuit model [5]. The effective permittivity and permeability of the dielectric substrate are utilized to be able to analyze the characteristic of the substrate. The loss (imaginary) components of the permittivity and permeability are neglected in these lossless cases. Up to now most studies have only focused on the wave propagation rather than the attenuation of the wave in the dielectric substrate. However, EBG structures also show ideal absorption within a frequency band when applied on a suitable lossy substrate [6]. The loss component creates a high attenuation and correspondingly a large absorption depending on the loss tangent.

In this paper an equivalent circuit model is introduced to model EBG structures on lossy materials, like in BiCMOS/CMOS silicon technologies. The model includes the conductivity of a lossy substrate. These EBG structures can be used to enhance the radiation efficiency of AoCs or to improve the quality factor of on-chip inductors. A square patch EBG structure is used as an example to analyze the variation of the reflection characteristics by changing the conductivity of the substrate. An accurate circuit model is used to show the relevant formulas of both lossless and lossy substrate in Section II. Section III shows how the input impedance of the EBG structure varies for different conductivity values of the substrate. To verify this model, results are compared with simulated data as described in Section IV.

II. The Lossless/Lossy Model

A. *High impedance surface on a lossless substrate*

Most of the investigations on HIS or EBG structures are focused on lossless substrates. An example of such a planar square patch EBG structure is shown in Fig. 1-(a) and consists of a metallic ground plane, dielectric substrate and a periodic metallic square.

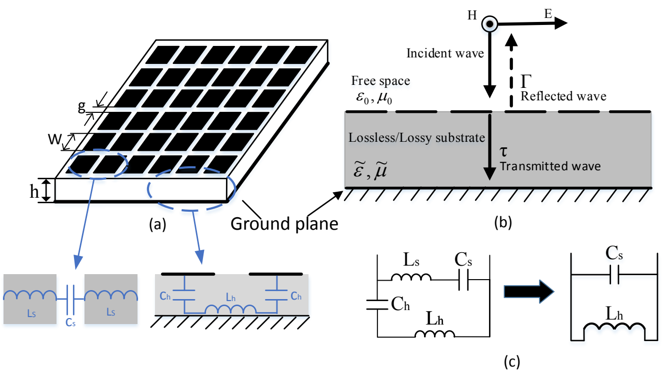


Fig.1. (a) Perspective view of a planar EBG structure. (b) The plane wave incident orientation on this EBG structure by cross view. (c) The equivalent circuit of this structure.

The square patch has a small series surface inductance L_s, which can be ignored compared to the series surface capacitance C_s caused by the adjacent patch. Also the surface of the square patch above the metallic ground plane at distance h acts as a capacitance C_h. The ground plane can be modeled as an inductor L_h by applying transmission line theory. The EBG structure is excited by an incident plane wave with the transmitted wave τ and reflected wave Γ as shown in Fig.2 (b). The overall circuit, including the capacitors (C_s, C_h) and inductors (L_s, L_h), is shown in Fig.3 (c). A more simplified parallel LC resonant circuit can also be achieved by ignoring the small capacitor C_h and inductor L_s.

The input impedance of the simplified resonant circuit can be expressed by:

$$Z_{in} = \frac{j\omega L_h}{1-\omega^2 L_h C_s} \tag{1}$$

This equation shows that a parallel LC circuit is inductive at low frequencies, and capacitive at high frequencies. The impedance goes to infinity at the resonant frequency $\omega_0 = 1/\sqrt{L_h C_s}$. Assuming the periodical square patch as the reference plane, the reflection coefficient characteristics are constituted by its magnitude and phase:

$$\Gamma = \begin{cases} |\Gamma| = \left|\dfrac{\widetilde{Z}_{in} - Z_0}{\widetilde{Z}_{in} + Z_0}\right| \\ phase = angle(\Gamma) \end{cases} \tag{2}$$

where $Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377\Omega$ is the characteristic impedance of free space.

From equation (1) and (2) we can find the frequency for which the real part of the input impedance is zero and for which the imaginary part is infinite. In this particular case, the reflection magnitude is equal to 1 and the phase equal to 0°. For the ideal lossless model, this EBG structure is a perfect magnetic conductor (PMC) within the defined frequency range for which the reflection phase is between -90° and +90°.

B. *Absorption behavior of lossy substrate metamaterials*

When a lossy substrate is used, the equivalent inductor L_h and capacitor C_s of Fig.1 have no longer real values, since the loss tangent (tan δ) introduces inherent dissipation in the lossy dielectric. The relation between the loss tangent and the conductivity of the dielectric substrate is given by:

$$\tan(\delta) \approx \frac{1}{\rho\omega\varepsilon_0\varepsilon_r} = \frac{\sigma^e}{\omega\varepsilon_0\varepsilon_r} \tag{3}$$

where ε_r is the relative permittivity of the dielectric material, σ^e is the electric conductivity and ω the angular frequency of the applied field.

The inductance L_h of the dielectric substrate can be directly derived from the transmission line theory:

$$\widetilde{L}_h = \frac{\widetilde{X}_L}{\omega} = \frac{\widetilde{\eta}_d \tan \widetilde{k} h}{\omega} \tag{4}$$

The complex-valued wavenumber $\widetilde{k} = \omega\sqrt{\widetilde{\varepsilon}\widetilde{\mu}}$ and the characteristic impedance of the dielectric substrate $\widetilde{Z}_d = \sqrt{\frac{\widetilde{\mu}}{\widetilde{\varepsilon}}}$ is derived from the permittivity and the permeability.

The complex permittivity and permeability ($\widetilde{\varepsilon}, \widetilde{\mu}$) can be expressed by:

$$\widetilde{\varepsilon} = \varepsilon_0\varepsilon_r + \frac{\sigma^e}{j\omega}, \quad \widetilde{\mu} = \mu_0\mu_r + \frac{\sigma^m}{j\omega} \tag{5}$$

The imaginary part of the permittivity σ^e/ω is related to the loss or dissipation of the energy in the medium. $\widetilde{\mu}$ is the permeability, σ^m is the magnetic conductivity and σ^m/ω is the loss in the medium. Since, in our case, we only consider electric losses, we will assume $\sigma^m = 0$ and the permeability remains real: $\widetilde{\mu} = \mu = \mu_0\mu_r$.

The capacitance generated by the narrow gap is now given by the expression [7]:

$$\widetilde{C}_s = \frac{(W+g)\cdot(\varepsilon_0 + \widetilde{\varepsilon})}{\pi}\log\left(\frac{2\cdot(W+g)}{\pi\cdot g}\right) \tag{6}$$

where W is the width of the square patch and g is the gap of the adjacent patches. The complex-valued input impedance Z_{in} of the planar EBG structure on a lossy substrate can be calculated from the derived complex inductance and capacitance:

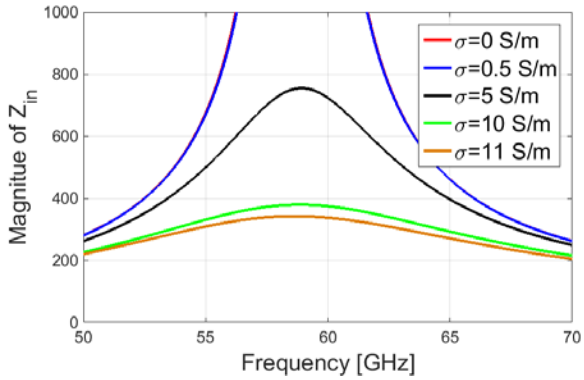
$$\widetilde{Z}_{in} = \frac{j\omega\widetilde{L}_h}{1-\omega^2\widetilde{L}_h\widetilde{C}_s} \tag{7}$$

III. ANALYSIS OF THE INPUT IMPEDANCE

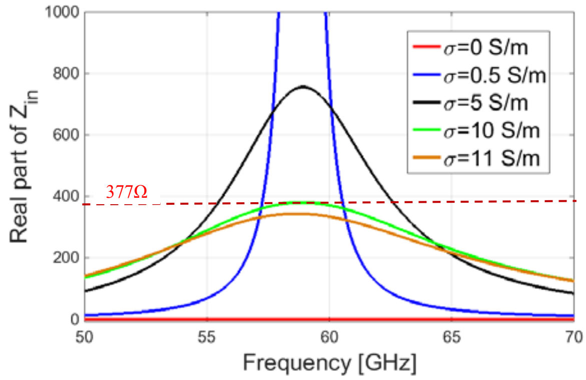
In the previous section, the input impedance of in case of an ideal lossless substrate is a pure imaginary number. When the conductivity is taken into account, the input impedance of the lossy substrate is expressed as a complex value characterized by a real and imaginary part:

$$\widetilde{Z}_{in} = \frac{j\omega\widetilde{L}_h}{1-\omega^2\widetilde{L}_h\widetilde{C}_s} = \mathrm{Re}\{Z_{in}\} + j\cdot\mathrm{Im}\{Z_{in}\} \tag{8}$$

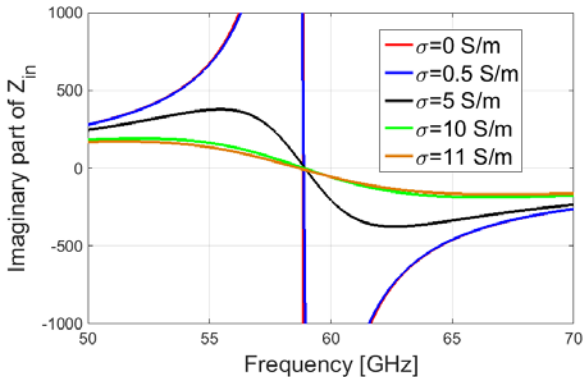
The square patch in Fig.1 is used to illustrate the influence of different lossy materials with respect to the input impedance of the planar EBG structure. In this work we use typical parameters from a main stream BiCMOS/CMOS Silicon technology [8]. The resistivity of the silicon substrate used in these two processes are not the same, for instance, the resistivity is about 200 Ω.cm for BiCMOS technology and 10 Ω.cm for CMOS technology. We will assume that the square patches are placed on a lossy silicon substrate with ε_r = 11.9 and thickness h = 200 μm. The dimensions of the planar EBG structure are listed as follows: W = 180 μm and g = 5 μm. Here, the conductivity σ of silicon is used as a variable and the other dimensions remain unchanged. Note that the typical value of σ = 0.5 S/m (corresponds to ρ = 200 Ω.cm of BiCMOS technology) for the technology in [8]. The planar



(a)



(b)



(c)

Fig.2. Analysis of the input impedance of EBG structure with different conductivity. (a) Magnitude. (b) Real part. (c) Imaginary part.

EBG structures are modelled and simulated with the help of a 3D electromagnetic full wave simulator tool CST MWS [9].

To show the variation of the input impedance more clearly, Fig. 2 presents the simulated results in, (a) magnitude, (b) real part and (c) imaginary part with different conductivities of the lossy silicon substrate. The magnitude of the input impedance decreases with increasing conductivity from 0 to 11 S/m as shown in Fig. 2 (a).

Fig.2 (b) and (c) show that the real part, Re $\{Z_{in}\}$ = 0 and Im $\{Z_{in}\}$ = Infinity only in the lossless (σ = 0 S/m) case, as described in Section II. A. When σ gets a real value, the Re $\{Z_{in}\}$ becomes a large value and Re $\{Z_{in}\}$ and Im $\{Z_{in}\}$ decreases with increasing value of the conductivity. At the resonant frequency, the imaginary part is zero for each conductivity value. This means that the reactance varies from inductive to capacitive at the specified resonant frequency. Actually, the conductivity determines the gradient of the imaginary part curve: a higher conductivity results in a more smooth transition across the resonant frequency.

Additionally, when the conductivity increases to 10 S/m (corresponds to the resistivity of CMOS technology), the real part of input impedance equals to the characteristic impedance (377 Ω) of free space as shown in Fig.2 (b).

IV. Performance of EBG Structure on Lossy Substrates

The performance of the planar EBG structure is analyzed effectively by analyzing the reflection characteristics. Using Eq. (8) we can write the reflection coefficient of the planar EBG structure as:

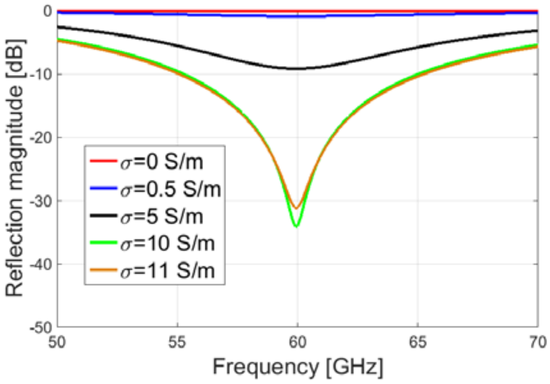
$$\Gamma = \frac{(\mathrm{Re}\{Z_{in}\} - Z_0) + \mathrm{Im}\{Z_{in}\}}{(\mathrm{Re}\{Z_{in}\} + Z_0) + \mathrm{Im}\{Z_{in}\}} \tag{9}$$

A. The reflection magnitude and phase calculated with Analytic Expressions

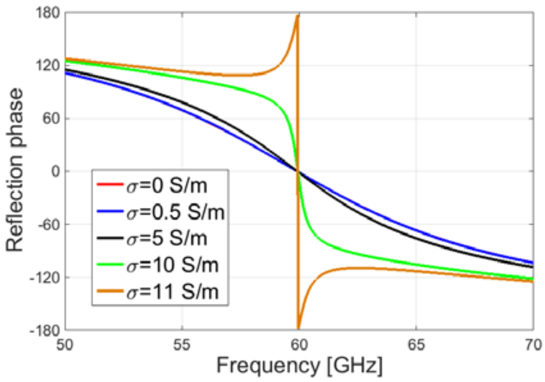
The calculated reflection characteristics of the square patch EBG structure with different electric conductivities of the silicon substrate is shown in Fig.3. The resonance frequency is 60 GHz. When σ = 0 S/m, the substrate will act as a lossless substrate, the EBG structure shows a perfect HIS performance. Its incident wave is totally reflected and the reflection phase is passing through 0° at 60 GHz with a 15 GHz bandwidth. However, when the conductivity increases to 0.5 S/m, around 90% (-1 dB) of energy is reflected with the same phase and only 10% is dissipated in the lossy silicon as shown in Fig.3 (a) and the bandwidth decreases as shown in Fig.3 (b). The planar EBG structure becomes a partial reflection surface when conductivity achieving 5 S/m. With increasing conductivity up to 10 S/m, Re$\{Z_{in}\} \approx 377\ \Omega$, $\Gamma \approx 0$, which means that all of the incident wave is transmitted into the dielectric material. In this case no energy is reflected and the EBG structure changes from a HIS to a perfect metamaterial absorber. That means that this planar EBG structure is not suitable for low-Ohmic CMOS technologies. When the conductivity is further increased to 11 S/m, the reflection magnitude becomes larger compared to the σ = 10 S/m case, and the $\Gamma < 0$, the planar EBG structure starts to show the phase characteristic of an electric ground plane (180 degrees).

B. The reflection magnitude and phase simulated with CST MWS

In order to verify our analysis of the EBG structure model for lossy substrates, it is essential to compare the results with more detailed simulations using an advanced EM simulator. Fig.4 shows the simulated results obtained with CST MWS. Compared to the calculated results from our analytical model,

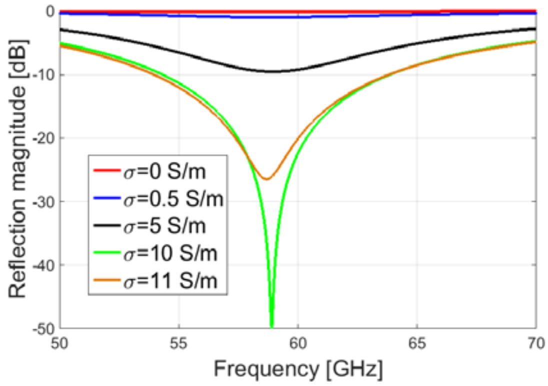


(a)

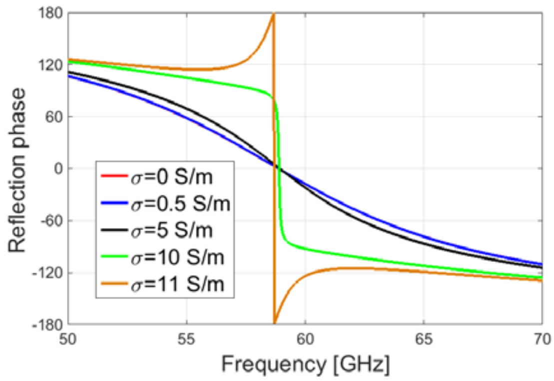


(b)

Fig.3. Calculated reflection characteristics with different conductivity by analytical expression. (a) Reflection magnitude. (b) Reflection phase.



(a)



(b)

Fig.4. Simulated reflection characteristics with different conductivity by CST. (a) Reflection magnitude. (b) Reflection phase.

the resonance frequency shows a 1 GHz shift approx. 1.67% with respect to the resonance frequency. The most important feature is that the variation trend, both in reflection magnitude and phase, show a very good agreement with the simulated results.

The small offset of the resonance frequency is due to the fact that we have ignored the small series surface inductance L_s and the capacitance C_h between patch and the ground plane in our model.

V. Conclusion

This paper provides some useful analytical expressions to analyze the model EBG structures placed on and lossy silicon substrates. An equivalent model is developed that includes the electric conductivity of the lossy substrate. According to the analysis of the complex input impedance, we have shown that the EBG properties vary from HIS to a metamaterial absorber with different conductivities. It is important that the conductivity or loss tangent of the substrate is considered to be added into the equivalent circuit model to determine the reflection characteristic of the EBG structure. Based on the reflection characteristic for different conductivities, the planar EBG structure provides an acceptable performance for BiCMOS technology, but cannot be used in mainstream CMOS technologies.

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