Optik 125 (2014) 6428–6435

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

A synthesis technique of single square loop frequency selective surface at terahertz frequency

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ARTICLE INFO

Article history:
Received 12 November 2013
Accepted 16 June 2014

Keywords:
Frequency selective surface
Square loop
Terahertz frequency
Transmission/reflection coefficient
Material losses

ABSTRACT

In this paper, we have explored and extended the use of frequency selective surface towards the terahertz regime of the electromagnetic spectrum where interesting applications such as imaging, sensing and communication exist. We have discussed a synthesis technique to design the single square loop frequency selective surface (SSLFSS) at 150 and 300 GHz which have found suitable application in the fast analysis and fabrication of the frequency selective surface. Moreover, the analytical results have been supported by the CST Microwave Studio and Ansoft HFSS commercial simulators. We have discussed the angular insensitivity of the SSLFSS at 150 GHz as well as 300 GHz. However, the specific problems arise at terahertz frequencies as compared to the radio and microwave frequencies are the ohmic losses. The proposed analysis has been extended from 100 GHz to 350 GHz to discuss the ohmic and dielectric losses. We have also discussed the other important issues which are very much significant in the terahertz regime of the spectrum such as skin depth and surface roughness.

1. Introduction

Recent consumption of the multimedia services and wireless networks is causing an explosive increase in mobile traffic, which demands the ultra-fast wireless communication systems. However, it is difficult to accomplish this demand through the advanced modulation schemes as well as signal-processing technologies and in order to satisfy the need of users, the recent advances in terahertz-wave (THz-wave) technologies have attracted attention due to the huge bandwidth and its potential for application in the wireless communications [1]. The frequency band of 275–3000 GHz, which has not been allocated for specific uses yet, is especially of interest to enjoy the full speed of future wired networks in a wireless environment, which will be around 10 Gb/s or even faster [2]. Recently, the use of frequency selective surfaces have expeditiously been increased in the antenna systems due to the gain and directivity enhancement [3–6] as well as to maintain the purity of the incoming wave at the receiving antenna where the Electromagnetic Interference (EMI) is the main hindrance [7–10], which is possible to achieve in a greater vicinity through operating the frequency selective surfaces (FSSs) in THz regime of the electromagnetic spectrum.

The frequency selective surfaces are resonant periodic arrays which exhibit selectivity in the frequency, polarization and the angle-of-incidence (AOI) [11]. However, in contrast to the electrical filters, the FSSs are spatial filters because the performance not only depends on the frequency, but also on the AOI wave as well as the polarization of the incident wave. These spatial filters are employed as plane-wave filters at radio frequency, microwave [12–14] and terahertz (THz) frequencies. There are numerous applications of THz band such as imaging [1], sensing [15], non-destructive tests, military as well as civilian security and the communications [16], where FSSs contribution is crucial. For the better understanding of the FSSs in the THz region, the prominent issue which requires an immense consideration is the ohmic losses/thermal losses [17]. However, the issue of ohmic losses, the power dissipation due to the presence of both ohmic and dielectric losses in relation to the power stored in the FSS region, the currents induced in the elements of the array has been discussed in few important studies. Moreover, amidst other aforementioned losses, the ohmic losses remain the prominent issue of discussion due to the resonant characteristics of the FSSs, which consist of metallic elements and have exhibit stronger absorption than a metallic screen, even though FSSs have less metallization per unit area [18].

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http://dx.doi.org/10.1016/j.ijleo.2014.08.009
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The purity of the incoming wave at the receiving antenna where the Electromagnetic Interference (EMI) is the main issue, which has been resolved in a greater vicinity through operating the frequency selective surfaces in THz regime of the electromagnetic spectrum [19]. Several researchers [20–23] have discussed the unique properties of the single square loop frequency selective surface (SSLFSS) in terms of the angular stability, cross polarization, bandwidth and band separation [24]. Therefore, in this paper, we have analysed and discussed the SSLFSS in THz region through the equivalent circuit (EC) model approach where the equivalent lumped parameters of a FSS is obtained due to the inductive and capacitive behaviour of the loop arms and the gap between the two loops. Moreover, in the absence of losses, the metallic elements represent capacitive screens and give rise to total reflection, while apertures in a metallic sheet represent inductive screens and give rise to total transmission [25]. However, in the microwave region, the losses arise from the propagation of incident wave inside lossy dielectrics dominates the effect of heat dissipation in the FSS structure [11] and in contrary to that, in THz region, the ohmic losses arise from the finite conductivity of the metallic elements increase significantly, which dominates the effect of heat dissipation in the FSSs [26]. However, the analysis of FSS depends on the physical parameters such as the periodicity (p) of the loop, loop dimension (d), width of the loop strip (w) and gap between two loops (g). Moreover, the p of the FSS elements must be chosen on such a way that the grating lobes do not appear at the frequency band of interest due to which the energy in the main transmitted and reflected harmonics has been reduced. However, in the analytical approach discussed in this paper, after fixing the aforementioned physical parameters, the value of associated inductance and capacitance has been calculated to find the resonance frequency of the SSLFSS. Moreover, we have discussed the dielectric loaded SSLFSS rather the free-standing FSS because the presence of dielectric substrate around the FSS may not only be required for the physical integrity of the FSS, also provides the stable reflection and transmission characteristics with the wide range of AOI wave as well as amend the fundamental resonance frequency [27]. Therefore, it is relevant to address the issues related to the ohmic and dielectric loss before the fully application of FSS in the THz communication system. However, to the best of our knowledge, the existing literatures in THz (0.1–10 THz) region have not discussed the parameter synthesis of the FSSs, which is very important to find the value of the physical parameter of the FSS such as SSLFSS in this paper, to meet the specific resonance frequency and bandwidth requirement.

In this contribution, a technique to synthesize the parameters of the SSLFSS and the thermal losses associated with SSLFSS in the THz regime of the spectrum has been discussed. Section 2 concerned with the analytical approach to obtain the physical parameters of the FSS. Section 3 discusses the results obtained by the analytical approach and commercial simulators such as CST Microwave Studio and Ansoft HFSS. Section 4 explores the effect of the AOI on the resonant frequency of SSLFSS terahertz regime of the electromagnetic spectrum. In Section 5, the ohmic as well as the dielectric losses and its effect on the reflection, transmission as well as on the absorption parameter have been discussed. Finally, Section 6 concludes the work and recommend its future considerations.

2. Principle of operation

The SSLFSS has been represented by an EC model, which has been used to extract the circuit lumped parameters such as inductance (L) and capacitance (C) by several researchers [28,29]. The EC model approach provides a platform to obtain the equivalent inductance and capacitance from the given physical parameters of FSS such as the p, d, w, g and AOI (θ). In Fig. 1(a), a FSS has been shown with aluminium as a metallic patch ($\sigma = 3.5 \times 10^7$ H/m) which is mechanically attached to the thermocol (relative dielectric permittivity $\varepsilon_r = 1.05$). However, in the design of an SSLFSS, it is desired to find the d and p of the loop to resonate at the specific frequency and to have the desired bandwidth. The existing literature only provide the knowledge about the value of the L and C for a given square loop but the accurately synthesis of the square loop from the knowledge of the resonance frequency is a challenging task and has not been dealt adequately in THz region. To overcome the synthesis difficulty of a SSLFSS, a simple novel mathematical expression to calculate the loop dimensions with the certain accuracy has been developed.

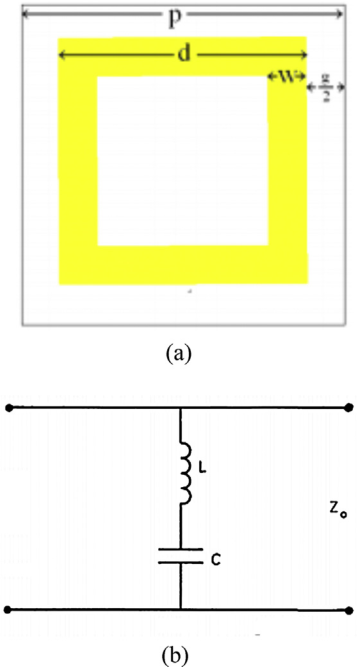

Fig. 1. Schematic of (a) the single square loop FSS and (b) its equivalent circuit model.

The EC of the SSLFSS comprises a single series LC circuit shunted across characteristic impedance (Z_0) of the free space as shown in Fig. 1(b). Moreover, for the incident field polarized parallel and perpendicular to the metallic strip, the EC elements are obtained by the following equations [30]:

$$\frac{\omega_r L}{Z_0} = \frac{d}{p} \cos\ \theta \cdot F(p, w, \lambda, \theta) \tag{1}$$

$$F(p, w, \lambda, \theta) = \frac{p}{\lambda} \ln csc \left(\frac{\pi w}{2p}\right) + G(p, w, \lambda, \theta) \tag{2}$$

and

$$\begin{aligned} \frac{B_c}{Z_0} &= 4\frac{d}{\lambda} \cdot \sec\theta \cdot F(p, g, \lambda, \theta) \\ \frac{\omega_r C}{Y_0} &= 4\frac{d}{\lambda} \cdot \sec\theta \cdot F(p, g, \lambda, \theta) \end{aligned} \tag{3}$$

$$F(p, g, \lambda, \theta) = \frac{p}{\lambda} \ln csc \left(\frac{\pi g}{2p}\right) + G(p, g, \lambda, \theta)\, e_{eff} \tag{4}$$

In Eqs. (1)–(4), e_{eff}, Z_0, Y_0, $G(p, w, \lambda, \theta)$ and $G(p, g, \lambda, \theta)$ are the effective dielectric permittivity of the medium, characteristic impedance in free space, characteristic admittance in free-space and the correction factors for associated inductance and capacitance, respectively. However, at the cost of minor sacrifice in the accuracy, Eqs. (1) and (3) may be re-written as follows:

$$\frac{\omega_r L}{Z_0} = \frac{d}{p} \cos\theta \cdot \frac{p}{\lambda} \ln csc \left(\frac{\pi w}{2p}\right) \tag{5}$$