# Electromagnetic characteristics of serpentine shaped metamaterial in terahertz region

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***Abstract-*** **In medical applications, a serpentine shaped metal electrode is widely used as the electrode of flexible and stretchable devices. Also, terahertz (THz) technology has been intense attraction for the medical applications due to the harmlessness to human body. Although the serpentine shaped metal electrode is used for bio-application electronic devices, it can also gain the electromagnetic characteristics through the resonance of geometrical inductance and capacitance. We therefore conducted a computational study of a serpentine shaped metamaterial (SSM) to investigate the electromagnetic response in THz using by commercial software (CST Microwave Studio). The detailed results will be discussed.**

## I. Introduction

Terahertz (THz) technology has been intense attraction for the medical applications such as high-resolution tissue imaging, cancer detection and dental care [1-2]. Electromagnetic metamaterials, which are artificial composite media with subwavelength unit cells, can be used as the medical devices due to the ability of manipulation on THz electromagnetic wave. In general, metamaterials can be considered as an LC equivalent circuit with the natural resonant frequency given by $\omega_0 = (1/LC)^{1/2}$, with L and C denoting the gemetrical inductance and capacitance of the metamataerials [3].

From this point of view, the electrodes of flexible and stretchable electronics can also obtain the properties of metamaterials since their dimensions of electrodes and THz metamaterials can be analgously designed. In terms of epidermal electronic devices, which are used for applications of health and wellness monitoring, the devices laminate directly on the skin, in a conformal manner, and so the electrode should be designed to be robust on the deformation of skin surface [4]. For this purpose, serpentine shaped metal electrode, which one of fractal-based electrodes, is widespread since it provides considerbly low effective elastic moduli and large deformability [4-5].

Although the serpentine shaped metal electrode is used for bio-application electronic devices, it can also gain the eletromagnetic characteristics through the resonance of geometrical inductance and capacitance. We therefore performed the simulation of serpentine shaped metamaterial (SSM) to study on the electromagnetic response of SSM. Frequency domain solver in commerical software (CST Microwave Studio) was used to estimate the frequency characteristics of SSM. The distributions of E-field and surface current flow were also obtained by this commercial software.

## II. Simulation Modeling and Resutls

Fig. 1(a) displays the simplified simulation domain in our study. We conducted the simulation in two port systems with Frequency domain solver as we mentioned. The direction of wave propagation is along the – z direction from Port 1 to Port 2. Fig. 1(b) shows the top view of SSM and magnified view of unit cell. The feature size of the unit cell was chosen with the following parameters: unit cell period with $L_x$ and $L_y$ = 43 um, outer radius $R_{out}$ = 12 um, inner radius $R_{in}$ = 7 um and the thickness of SSM is 2 um as shown in Fig. 1(b). In order to establish infinitely extended metamaterials, we chose the unit cell boundary, which repeats a meta-atom infinitely along the x and y directions. Silver was used as the material of SSM and substrate was not used (i.e., substrate is air).

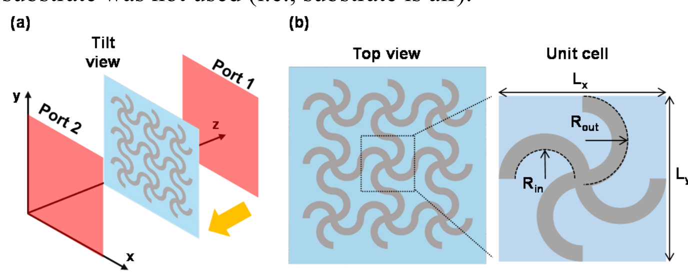


Fig. 1. (a) Schematic of simplified simulation domain in our study. The light propagates from Port 1 to Port 2 along the – z direction. (b) Top view of SSM and magnified view of unit cell. The magnified view exhibits dimensional parameters of SSM.

Fig. 2(a) demonstrates simulated co-polarized transmission and reflection spectra, which are identical incident and transmission or reflection polarization states, as a function of the frequency and polarization state of incident wave. The result shows that the pass bands of transmission spectra for each polarization state are obtained at the frequency of 3.34 and 7.80 THz regardless of incident polarization states. In terms of reflection spectra, weak reflection points, which are nearly zero, are observed at these frequencies. Interestingly, the pass band at the frequency of 3.34 THz exhibits wide-band property compared with that of at the frequency of 7.80 THz. To further study this phenomenon, we conducted simulations of E-field distribution as shown in Fig. 2(b). At the frequency of 3.34 THz, the strong elecrtric fields are observed on both sides of the dotted line in figure irrelevant to the polarization states. On the other hand, at the frequency of 7.28 THz, the greenish E-field distributions, which are almost zero, are found below the lines as the values of transmission are 0.017 and 0.016 for the x-

978-1-4673-8603-6/16/$31.00 ©2016 IEEE

polarized and y-polarized incident wave, respectively. In the case of frequency of 7.80 THz, the electric field distributions are significantly diffracted and scattered compared to that of another pass band (i.e., 3.34 THz), while intense electric field distributions are observed on both sides of the dotted lines regardless of the polarziation strates. These results indicate that the bandwidth is related with the field distribution.

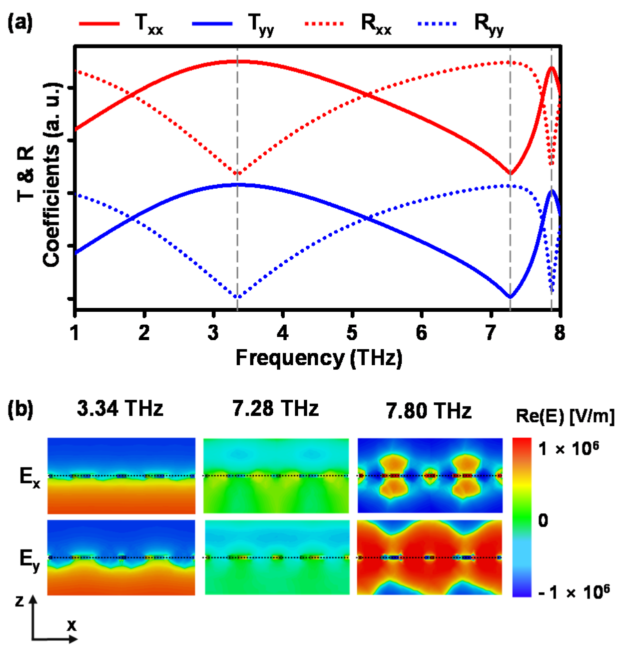


Fig 2. (a) Simulation transmission and reflection spectra of co-polarized THz wave. (b) Distributions of the (top) $E_x$ and (bottom) $E_y$ with a phase of 0° at the frequency of 3.34, 7.28 and 7.80 THz for the x-polarized and y-polarized incident wave, respectively. The dotted lines in contour plots indicate the position of SSM.

In nature, materials which can change the polarization state of incident wave are ubiquitous from molecules and polymers to crystals. This effect results from the chirality of materials, which refers to structures with any mirror asymmetry planes [6]. Due to the fact that polarization conversion (PC) is caused by geometrical effects of molecules or lattice of materials, metamaterials can offer much stronger PC than that of natural available materials as it can be geometrically designed to obtain strong chirality. To investigate the characteristic of PC in SSM, we performed additional simulation. Fig. 3(a) illustrates cross-polarized transmission spectra of single layer and double layer as the function of frequency. This results show deeply weak PC efficiency in the single layer due to lack of chirality. On the contrary, double layer of SSMs, where upper layer located 3um above from the bottom layer is rotated 180° at the y-axis, exhibits considerable strong PC efficiency owing to the intense chirality. To understand this phenomena, we conducted another simulation, surface current flow, at resonance points for each spectra (i.e., A and B in Fig. 3(a)). In the case of single layer, surface current is focused on the center of SSM, the strong surface current, however, is found at the edge of SSM along the direction of cross-polarized in the case of double layer.

To integrate several functions into an epidermal device, additional electrodes are mostly needed. From this point of view, strong PC efficiency can be occurred as we shown above.

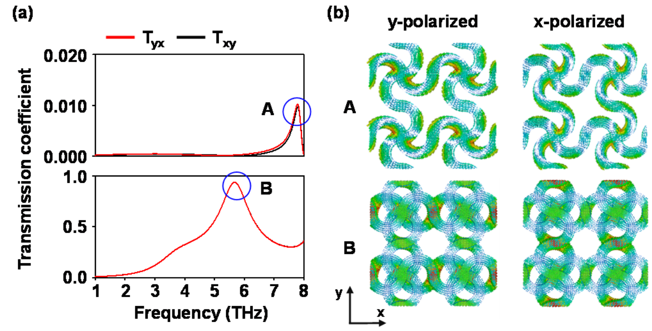


Fig 3. (a) Simulation results of cross-polarized transmission coefficient for serpentine structure with (top) single layer and (bottom) double layer. (b) Distributions of surface current flow in the xy plane with the position of z = 1 at the resonance points (i.e., A and B in Fig.3 (a)) for the polarization state of incident wave.

## III. Conclusion

In summary, serpentine shaped metamaterial (SSM) was investigated by simulations to examine the electromagnetic response. Although this structure is widely used as the electrode of various flexible and stretchable electronics, SSM can also provide the characteristics of metamaterials. Our results demonstrate that SSM can be used both a filter and polarization converter in THz range. The results in this paper can be useful to design diverse flexible and stretchable electronics for medical applications.

## Acknowledgment

This work was partly supported by the Basic Science Research Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (2014R1A1A1005945), and by supported by MSIP as GFP / (CISS-2013M3A6A6073718).

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