

Chapter 2

A Study of Tunable Metamaterial Devices for the THz Region

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Abstract In order to cope with the “THz Gap”, metamaterial based devices operating at about 1 THz have been designed to have a tunable response. We studied the electromagnetic behaviour of periodic structures consisting of different “unit cells” based on the concept of Split Ring Resonator (SRR). The devices response in the required frequency region is simulated using a commercial electromagnetic code. Different modulation mechanisms have been investigated, including the use of liquid crystals, MEMS, semiconducting substrates.

2.1 Introduction

During the last two decades substantial progress has been achieved in the development of THz science and technology. However, there are several restrictions which limit the full exploitation of fruitful applications covering this frequency region. One of the main constraints is the so called “THz Gap”, which is basically due to the lack of appropriate response at those frequencies for many naturally existing materials. This problem can be solved using artificially structured electromagnetic materials, named metamaterials, typically comprised of periodic arrays of sub-wavelength metallic structures within or on a dielectric or semiconducting substrate. The use of this type of material, on an appropriate form such a Split Ring Resonators (SRR), could find application for the development of novel devices operating in this frequency region and aimed at filtering, modulating, and switching the electromagnetic signal. Since the first extensive studies on metamaterials, the attention of most researchers has been focused on the linear properties of these composite structures.

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However, to achieve the full potential of the unique characteristics of metamaterials, the ability to dynamically control the material properties or tune them in real time, through either direct external tuning or nonlinear response, is required. Here we have studied and compared different strategies in order to achieve tunability in the THz region, including the use of liquid crystals, MEMS, and semiconducting substrates [1–5].

2.2 Liquid Crystal

The proposed tuning system is based on the use of a liquid crystal (LC). Its properties can be controlled reorienting the LC molecular director, described by the angle θ , in respect to the oscillating electric field direction. LC molecules reorientation can be done using a static or slowly-varying electric field, by applying a magneto-static field or even using thermal control. Since the LC is the key element for this kind of tuning system, and in order to take full advantage of it, our study was focused on the influence of the LC intrinsic parameters and its interaction with the metamaterial unit cell to achieve the highest tuning performance. For this reason, two LC configurations were used. The first standard configuration implies the use of an appropriate amount of LC top layer covering the SRR (Fig. 2.1(a)) whereas the second one is based on the use of the LC in between two metallic structures. In such a case, a first SRR, the LC layer and then a second SRR are combined to give a sandwich configuration, as shown in Fig. 2.1(b). The use of a support to hold the second SRR suspended is compulsory, and several materials can be used for it, like the PI-5878G (HD Microsystems).

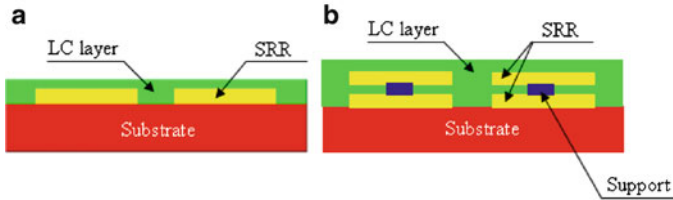


Fig. 2.1 LC configurations: (a) the LC top covers the metallic structure; (b) the LC is in between two metallic structures

The tunability of the designed system is represented by the shift of the resonance frequency plotted in the S_{21} parameter curve. LC properties are changed according to [6]. For those calculations, the LC under evaluation is represented as an anisotropic materials with an ordinary optical index $n_o = 1.38$, an extraordinary optical index $n_e = 1.43$, and thus a birefringence of 0.05. Therefore, in our simulations the LC layer permittivity is considered as [2.0449, 1.9044, 1.9044] and [1.9044, 2.0449, 1.9044] respectively for two orientations: $\theta = 0^\circ$ and 90° . We also used a variable parameter s representing the difference between the ordinary and the

extraordinary permittivity, so that the LC layer is treated as $[\epsilon_x - s, \epsilon_x + s, \epsilon_z]$. Loss tangent values were set as $\tan\delta_o = 0.020$ for n_o and $\tan\delta_e = 0.016$ for n_e .

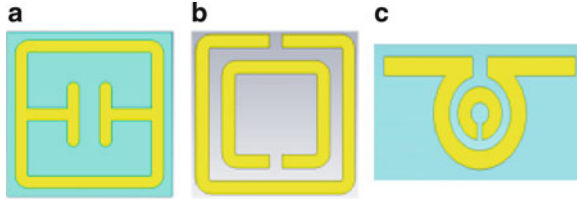


Fig. 2.2 SRR based geometries: (a) double SRR with large internal gap, (b) double SRR, (c) modified “omega” shaped SRR

We started by modelling periodic structures consisting of different “unit cells”, with different Split Ring Resonator (SSR) based geometries [4, 5], as shown in Fig. 2.2. Several simulations were performed using CST, a commercial electromagnetic code, in order to see the device response in the required frequency region. In Fig. 2.3, the scattering parameter S_{21} vs frequency is plotted for the double SRR with internal large gap geometry reported in Fig. 2.2(a). The resonance frequencies depend on the chosen geometry and are located within the range between 4 and 8 THz for the same SRR dimensions. A much larger shift is observed in the sandwich configuration compared the top layer one with a significant modulation of the response (2.3% and 0.5% respectively).

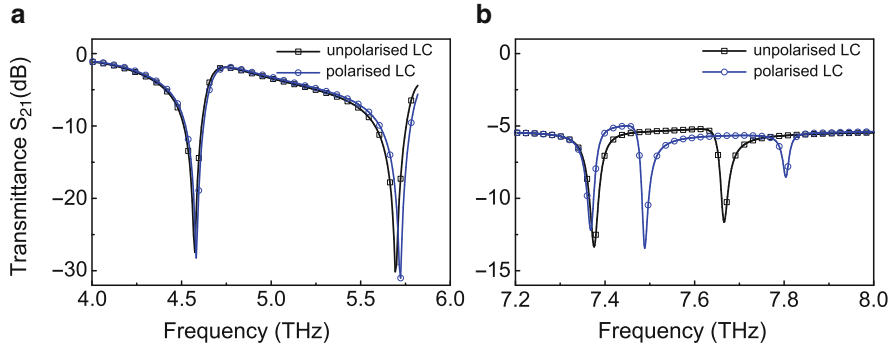


Fig. 2.3 Simulation results for the double SRR with large internal gap and LC tuning system: (a) top LC layer configuration, (b) sandwich LC configuration

2.3 MEMS

The second tuning system we decided to investigate is based on Micro-Electro-Mechanical Systems (MEMS). In this case, the frequency tuning mechanism is based on the change of the split size or on the creation of new splits, as shown

in Fig. 2.4(a) and (b) respectively, which induces the variation of the gap size and the increase of the overall capacitance of each unit cell. The split size modification can be based on the lateral movement of a MEMS comb drive implanted in the active area.

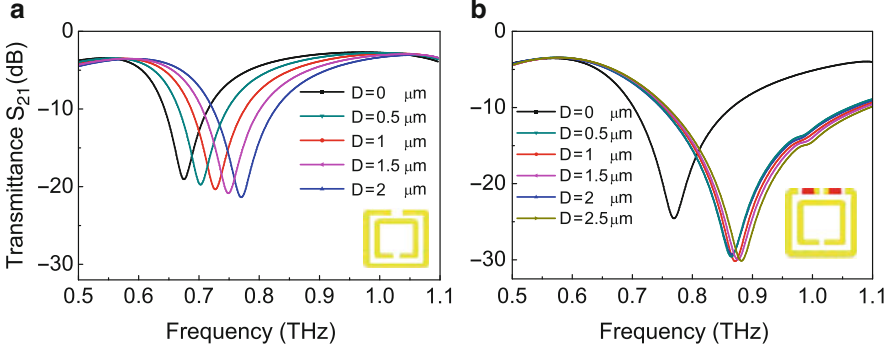


Fig. 2.4 Simulation results for MEMS based double SRR: (a) with gap size variation, (b) creation of additional gaps

For the first case (Fig. 2.4(a)), where there is only the gap variation, we can see a uniform frequency shift up to 14%. In the second case (Fig. 2.4(b)), we observe a large frequency variation (approximately 15% shift) for the first displacement D of 0.5 μm , since this implies the creation of new gaps (capacitances) in the active area. This variation is then followed by a uniform shift due to the continuous displacement of the MEMS from 0.5 μm to 2.5 μm . This translates in a further 1.9% frequency shift. This method provides a good frequency tuning preserving a high performance signal at the same time.

2.4 Semiconducting Substrate

This technique has been recently used as tuning mechanism for the THz region. It shows a good overall performance and offers a variety of methods which can be used to realise the change in the substrate conductivity. A first one [7] is based on the implantation of a silicon layer in the gap region. Changing its conductivity σ in the region near the surface by laser exposure, one can control the frequency shift using the laser energy variation. An alternative method uses the Schottky diode principle in order to change the substrate conductivity by creation of a depletion region in the active area of the unit cell [4]. In this case the tuning mechanism is given by a dc or slowly varying bias electric field. Figure 2.5 shows the simulation results for this type of tuning system, applied to a metamaterial where the unit cell is given by the pattern shown in Fig. 2.2(c). In this case, the observed shift is close to 7% relatively to the central resonant frequency.

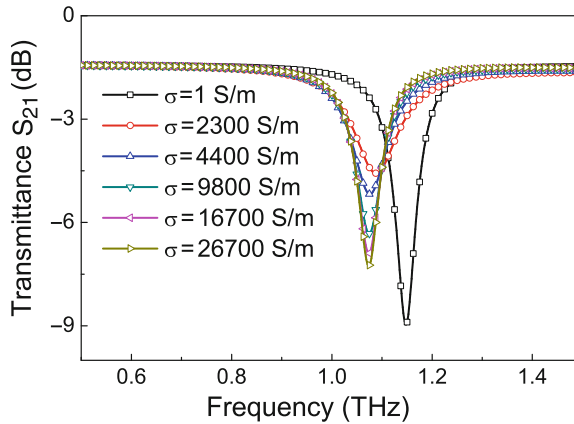


Fig. 2.5 Simulation results for the conductivity based tuning system

2.5 Conclusions

A number of mechanisms have been proposed and studied that allow a significant variation of the electromagnetic response of metamaterials operating in the THz region and based on resonant metallic substructures. Presently, the most promising ones seem to be those based on micro-electro-mechanical systems or on semiconducting substrates, both electrically controlled. The mechanism based on the use of liquid crystals allows a “rigid” shift of the electromagnetic signal without modifying its overall profile and is also more flexible towards the nature of the external control (that can be electric, magnetic, thermal), however it is less effective in modulating the frequency response of the metamaterials under study.

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