Design of Multi-Layer Metamaterial in Terahertz Response

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Abstract:- The development of terahertz (THz) technology, which has the electromagnetic spectrum frequency between microwave and infra-red regions has attracted much research attention. However, due to various challenges in detection, generation and measurement of the THz waves, intense research have been carried out to enhance and tune the THz waves in order to close the 'Terahertz gap'. One of the important ideas is to use metamaterial with Split Ring Resonators (SRR) scaled to the sub-THz wavelength size to obtain different THz resonance responses. SRRs produces the desired magnetic susceptibility (magnetic response) in various types of metamaterials.

With the help of SRR, novel THz devices can be used in various applications such as THz filter. In the proposed work, SRR ring is designed & simulated using Polyethylene naphtha late (PEN) substrate which is 100 µm in dimension. Transmission spectra responses with tunable resonances are obtained using these metamaterials. By stacking all the substrates together, a multiband THz filter at 0.3626THz is obtained. The bandwidth of this simulated filter compared to the single resonance response is 4.3 times bigger. According to the results, it shows that the SRR inside the stacked metamaterial are excited towards certain frequencies within the multiband response. Because of the stacking of more than one SRR layers there is improvement in the resonance properties. Multi-layer metamaterial provides tuning property for multiband THz devices.

The above discussed structure is designed and simulated by Finite-integration time-domain using commercial software CST Microwave Studio 2014.

Keywords: *-CST studio, Metamaterials, Multiband applications, PEN substrate, split ring resonators, THz filter*

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1. INTRODUCTION

Metamaterials are materials engineered to have properties that have not yet been found in nature. They are made from assemblies of multiple elements fashioned from conventional materials such as metals or plastics. The materials are usually arranged in repeating patterns, often at microscopic or smaller scales that are smaller than the wavelengths of the phenomena they influence. Metamaterials derive their properties not from the properties of the base materials, but from their designed structure. Their precise shape, geometry, size, orientation and arrangement gives them their properties. Metamaterial research is interdisciplinary and involves such fields as electrical engineering, electromagnetics, classical optics, solid state physics, microwave and antennae engineering, optoelectronics, material sciences, nanoscience and semiconductor engineering. Negative index materials were first described theoretically by Victor Veselago in 1967 [1]. He proved that such materials could transmit light. He showed that the phase velocity could be made anti-parallel to the direction of Poynting vector. This is contrary to wave propagation in naturally-occurring materials. The electromagnetic (EM) responses from metamaterials has played an important role in the THz range, where other conventional materials exhibit weak electromagnetic response to the THz wave. Terahertz metamaterials interact at terahertz frequencies, usually defined as 0.1 to 10 THz. Terahertz radiation lies at the far end of the infrared band, just after the end of the microwave band. This corresponds to millimeter and submillimeter wavelengths between the 3mm (EHF band) and 0.03mm (long-wavelength edge of far-infrared light). With the development in metamaterials, metamaterials are believed to close the THz gap. Usually while using metamaterial, split ring resonators are being used. A split-ring resonator (SRR)is an artificially man-made structure which provides the required magnetic susceptibility (magnetic response) in different types of metamaterials ranging up to 200 terahertz. These type of resonators create the required strong magnetic coupling to an applied EM field, which is not possible to the other naturally available conventional materials. Split ring resonators (SRRs) comes in different dimensions and shapes. The best suited shape of a split ring resonator is a pair of rings usually square shaped. SRRs can produce an effect of being electrically smaller when responding to an oscillating electromagnetic field [2]. These resonators have been used for the combination of different left handed and negative refractive index medium, to realize the characteristics of the left handed metamaterial, it is essential to fabricate periodic metallic resonator structure called split ring resonators or wire cuts which were first introduced by Pendry et.al. [3] Using SRR, various design structures are been demonstrated. Many useful THz metamaterial devices, such as switches [4], modulators [5], perfect absorbers [6] and filters [7], were successfully practiced.

SRR based THz metamaterials shows narrow band magnetic and electric responses. This limits the performance in multiband applications. Many designs were made to broaden the terahertz related metamaterial outcomes [8] [9]. However, multi-resonance performance of planar metamaterials is usually accompanied by a compromise in resonance strength due to lower resonator densities at a given resonance frequency and the coupling among different resonators [10]. Furthermore, the miniaturized structures can affect the expected response by weakening and suppressing it [11]. However, the design of THz structures are been performed mainly on semiconductors or glass. Therefore, designing THz based metamaterial structures on plastic substrates and then stacking those metamaterials together can enhance the 3D THz metamaterials [12].

In the proposed work, we present split ring resonator based terahertz metamaterials in order to get the multiband response performance. Here, the layers of metamaterial having different dimensions and resonance responses are stacked together i.e. a multi-layer structure is designed to get a multiband THz output. It shows that multi-layer THz metamaterials provide a high performance multiband filter with a compact dimension and low cost.

2. DESIGN APPROACH

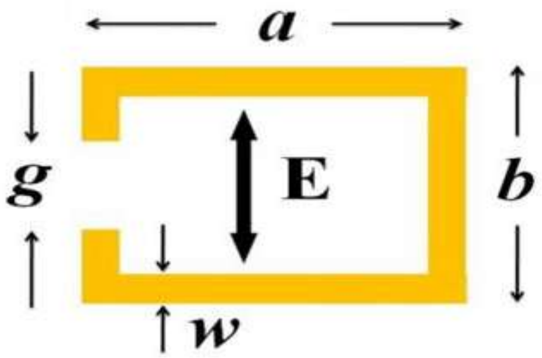

Fig 1: Basic Structure of the SRR Unit Cell

Figure 1. shows the geometry of the basic SRR with one ring structure. For every resonator, the length for the gap-bearing side is fixed at **b**= 50 µm and the gap size is fixed at **g** = 10 µm, while the length for the side perpendicular to**b** is set as **a** = 40, 50, 60, 70 and 80 µm from SRR1 to SRR5. SRR metallic line width is defined as **w** = 3 µm. Electric field **E** is parallel to the gap bearing side **b**.

The designed structure shown in Fig.2 is the ring of the basic split ring resonator. Polyethylene naphtha late (PEN) substrate is been used. The PEN substrate is very thin.It offers high flexibility and very useful for surface applications which are not in one plane. It gets easily wrapped around a cylinder with smaller than 1 cm diameter. This feature can be very useful for simulating and fabricating THz devices such as cloaking devices. The substrate has thickness of 6µm with dielectric constant $\epsilon_r =$ 2.56, loss tangent 0.003 and has dimension of 100×100µm. The design is carried out onFinite-integration time-domain using commercial software CST Microwave Studio 2014 as illustrated in Fig.2 (a), (b).

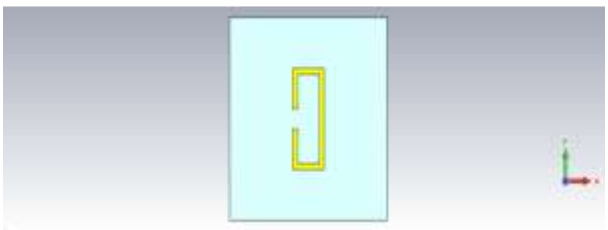

Fig.2 Designed Unit Cell Structure

3. SIMULATION RESULTS

Analysis and Simulation of proposed structure is carried out with the help of a simulation software. The proposed work was modeled and simulated using Computer Simulation Suite (CST MWS), an electromagnetic simulation software tool for high frequency ranges which is based on finite element modeling method(FEM). It provides the choice of simulator or mesh type to solve a particular problem. This may also be chosen for narrow band problems or when the use of tetrahedral grids is required.

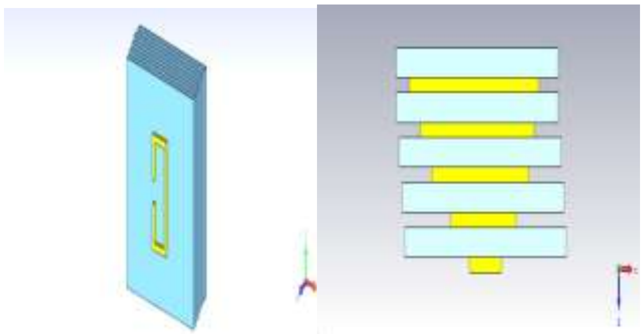

Fig 2(a) (b): Stacking of multi-layer metamaterials from SRR1 to SRR5

Time domain solver module is to calculate S-parameters. The Frequency domain solver usually is fastest when only a small number of frequency samples need be calculated. Hence, a broadband S-parameter simulation with adaptively chosen frequency samples is performed to minimize the number of solver runs. Any dealing with electromagnetic problems in high frequency range is preferred to be solved with CST because it is suited to the best and efficient analysis and design of components. With its three-dimensional approach, it can solve virtually high frequency field problems. This software contains several different simulation techniques, which are- Transient solver, Frequency domain solver, Integral Equation solver, Eigen Mode solver, multilayer solver and Asymptotic solver [13].In this design, transient solver i.e. time domain is being used.The transient solver delivers broadband frequency domain results like S-parameters. These simulations can be performed with an arbitrarily fine frequency resolution without extra computational cost, thus avoid missing single resonances inside the spectrum. Field results for many frequencies (for example 100 far field samples) can be derived from one single simulation run.

Transmission spectra(dB) were obtained which indicates that proposed structure is most suitable for terahertz devices. The Transmission spectra S_{21} of the split ring resonators with different side length **a** is shown in Fig.3.1 It is observed that the LC resonancefrequencies are at 0.697, 0.602, 0.532, 0.478, 0.434 THz for**a** = 40, 50, 60, 70 and 80 µm, respectively.

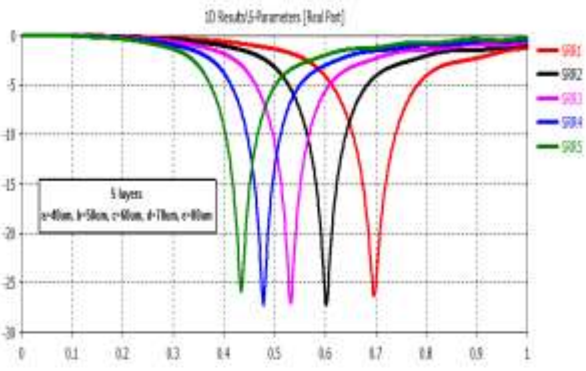

Fig 3.1 Transmission spectra of individual samples in THz

A shift in the LCresonance frequency is observed when the side perpendicular to **b**changesfrom 40 to 80 µm. This is expected since the split ring resonator having dimension less than the wavelength of lightfundamentally acts as a LC resonator circuit with $\boldsymbol{\omega_{LC}} = (\mathbf{LC})^{-1/2}$, where the inductance**L** points to the effective enveloped area of the SRR and the capacitance **C** is found out by the gap size and the surrounding medium between them . The increase in the side length larges of the close off or enveloped area and increases the inductance of the resonator, therefore there is an increase to the resonance frequency shift. Meanwhile, there is a narrowerresonance dip with increasing side length a, which matches with our simulation results. The full width at half maximum (FWHM) changes from 0.08442, 0.07675, 0.07147, 0.06651 to 0.06347 THz as **a**increases from 40 to 80 µm.

Structure	a(µm)	f_{LC}(THz)	FWHM(THz)
SRR1	40	0.697	0.08442
SRR2	50	0.602	0.07675
SRR3	60	0.532	0.07147
SRR4	70	0.478	0.06651
SRR5	80	0.434	0.06347

The outcome of a 2-layer configuration as shown in Fig. 3.2 which is first simulated in order to find out whether the frequency positions and intensity for each resonance are showing some affects or not. Two resonators SRR1 and SRR5 are taken and stacked together. Also, the specific positions of the two SRRs are matched so that they have the same incident wave and polarization. It is observed from the 2-layer transmission configuration that two different resonance dips are shown clearly at 0.402 and 0.615 THz. Because of stacking the resonance frequency is decreased and we get compact sized structure. Different from the other conventional resonance structures, the strength of the resonance response is not weakened. Therefore, we can conclude that multi-layer metamaterials have the capacity to increase the split ring resonator based metamaterial operation without distortion of other responses.

Furthermore, all the five SRRs with different **a** values are bonded together in sequence from SRR1 to SRR5 with SRR1 on top. This orientation is said to beappropriate in a THz system.The transmission spectra of the combined overall 5-layer metamaterials is shown in Fig.3.3. The positions of the five resonance dips in the overall frequency response match with the resonance dips from individual split ring resonators.The FWHM of this filter is measured to be 0.3626 THz which is about 4.3 timesgreater than the FWHM of SRR1 (a = 40 µm) and 5.7 times greater than thatofSRR5 (a = 80 µm). This shows that a large distance broader multiband response is achieved the simply stacking the resonators together.

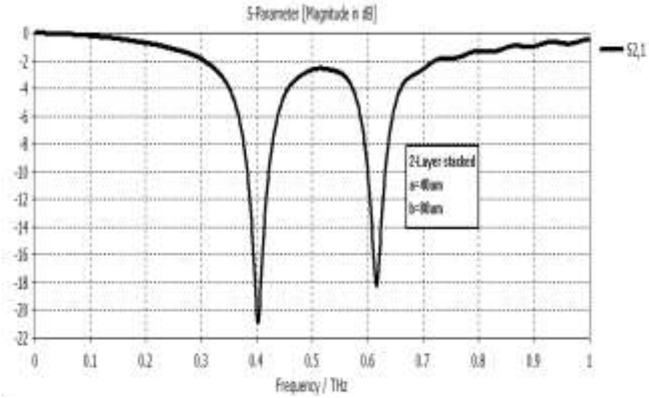

Fig. 3.3 2-Layered Stacked Metamaterials

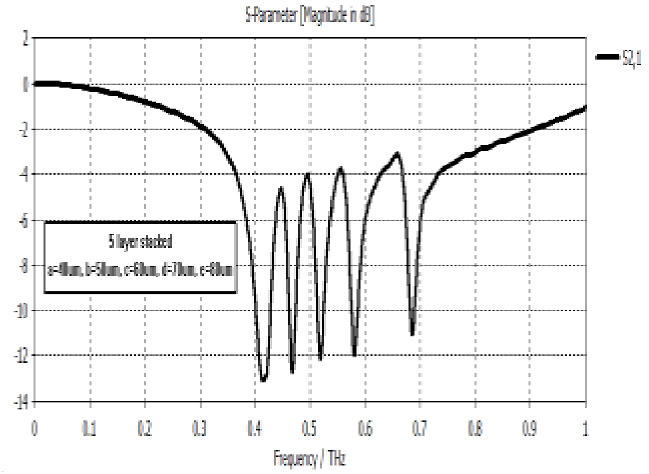

Fig. 3.3 5-Layered Stacked Metamaterials

4. CONCLUSION

In the proposed work, a SRR metamaterial structure is been designed and simulated in THz response by using CST MWS software. Transmission spectra is being reported by simulating individual sample structures, 2-layer stacked metamaterial structure and 5-layer stacked metamaterial structure responses. By changing the dimensions of the structure, it can be made to resonate for different applications. Different dimensioned split ring resonators with resonance frequencies of 0.434, 0.478, 0.532, 0.602

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and 0.697 THz are simulated on 100 μm flexible PEN substrate. A multiband filter with a combined bandwidth of all stacked sampled frequency responses is calculated to be 0.3626 THz. Simulation results concluded that the split ring resonator stacking within the multi-layer metamaterials are particularly excited towards certain specific frequencies inside the multiband response which makes the resonance properties of the overall response stronger. Multi-layer metamaterials have very useful applications in building functional multiband THz devices.

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