The Design of Split Ring Resonator (Srr) Based Terahertz Bandpass Filter and Comparison of Various Types of Filters.

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Abstract. Terahertz (THz) research has practiced an amazing progression in the past two decades. Terahertz filters play a key role in THz applications. Terahertz filters with high bandwidth, tunable center frequency, and low insertion loss are the challenging design. This article comprises the investigation of the frequency response of terahertz filters using various metamaterials, frequency selective surfaces, and parallel plate waveguides. The proposed work includes the design of SRR based terahertz bandpass filter with tunable center frequency and bandwidth. Also, the proposed THz filters is simulated using the Comsol software and the simulated results are observed. This proposed design is used for numerous applications like spectroscopy, wireless communication, and imaging, etc.,

Index terms: Terahertz frequency, Bandpass filter, Split Ring Resonator.

I. Introduction

THz wave ranges from 0.1 to 10THz with the wavelength lies between 30µm to 3mm [1,2]. As of late, the terahertz (THz) field has shown a broad scope of uses, for example, spectroscopy, communication, sensing, imaging, science, medication, etc [3-5]. Research on THz devices, for example, polarizers, modulators, switches, waveguides, antennas and bandpass filters are especially significant for uses of THz innovation. [6-16]. Metamaterials (MMs), have unique properties compared to other materials available in nature don't have, for example, negative refractive index, an electromagnetic induced transparency (EIT) and artificial magnetism have been a hot topic in THz region [17-20]. Parallel plate waveguide (PPWG) is a feasible frequency or wavelength determination device which can improve the terahertz imaging nature. Since the all the devices can couple free-space terahertz wave and with low transmission loss [21-23]. With the quick advancement of terahertz innovation, it turns out to be very important and dreadful for controlling the terahertz wave transmission effectively. THz wave filters are the basic control device in terahertz detecting, imaging framework and communication. Terahertz filters are used to select or reject particular band of frequencies in the band on 0.1 to 10THz.

Mohammad Azimbeik and et.al [24] proposed the graphene-based high pass filter(HPF), structure depends on a transmission line with short circuit stubs. Configuration utilizes optimum distributed HPF technique, design shows 0.1dB Bandpass Ripple, low insertion under 1.5dB and constant group delay 0.16ps. This structure depends on the impedance of all arranged stub, the characteristic impedance of the primary line and center transmission line. The Transmission line impedance is dictated by Chebyshev type response, width, and length of the line is significant. The power-current methodology is used to find the transmission line characteristic impedance. Optimum distributed HPF technique is utilized to arrive at the minimum bandpass attenuation. Filter shows the cut-off frequency of 5THz, has low loss and no bandpass ripples.
Jiu-Sheng Li and et.al [25] proposed and investigated the Terahertz Bandpass filter (BPF) based on frequency selective surface. Design uses Double layer frequency selective surface and fabricated by laser technology. The result shows the center frequency of 1THz and bandwidth of 440GHz. The main drawback of the proposed structure is the operating wavelength is not tunable. Proposed design uses rectangular hole arrays on the double-layer, three-layer and four-layer design produce high insertion loss in the smooth passband. The design is manufactured on the tin foil of 10μm and misfortune digression 0.002 by utilizing an ultrafast high-force laser framework.

A. Beheshti Asl and et.al [26] designed and simulated a multilayer metamaterial-based THz BPF. They investigated the bilayer metasurface filtering property compared to a unit cell of single bilayer cylinder. If number of cylinders increases, bandwidth of the filter increases, by changing the dimensions of basic element, center frequency becomes tunable. The proposed system as the advantages of wideband, tunable, and easy to construct, a bandwidth of 1THz and transmittance is 93%. In Bilayer metasurface, substrate is made up of silicon dioxide (SiO2) and the top layer of the cylinder is coated by a thin layer of gold with 0.2µm.

Kehui Jia and et.al [27] demonstrated THz narrow BPF based on stopband modulation in corrugated PPWGs. The Junction of two stopbands is used to design a bandpass filter. When two stopbands are brought closer by adjusting the plate distance and adjusting depth of the groove, which forms the narrow bandpass region. The period of two stopbands is varied by the distance of two plates. The filter can accomplish a scope of zero-sideband, high transmissivity (T=99.8%), thin line width(5.8GHz), and high-quality factor. In the parallel plate waveguide structure, two parallel plates of thickness ‘t’ are placed closer. Plate materials are perfect conductors and use Silver (Ag). The dielectric material with low loss is used as a waveguide, with a refractive index of ‘n’ and the separation between plates is ‘g’. The inward exteriors of two silver plates are carved with rectangular channels with a time of p. The width and depth of the sections are w and h.

Tao Gao and et.al [28] employed the structure of cascading frequency selective surface (FSS) which increases the frequency selectivity and roll-off rate of terahertz BPFs. The resonant coupling between FSS layers roots peculiar transmission crests. The Double-layer FSS is analyzed using its equivalent circuit model. FSS structure is obtained using metal foil by creating regular apertures on it. This design has a tunable center frequency, low insertion loss, and also easy to design. Double layer FSS has many advantages compared to single-layer FSS like good frequency selectivity, lower angle sensitivity, greater roll-off rate and also appropriate for multiband and narrowband operation.

Dandan Sun and et.al [29] demonstrated THz broadband bandpass filter using electromagnetically induced transparency (EIT) structure with complementary metasurface. This design is based on single-layer metal-dielectric metamaterial and has more advantages compared to multi-layer metal-dielectric metamaterial structure. The result shows a 3dB bandwidth of 27%, the center frequency of 0.405THz. By converting the filters metal pattern into its complementary structure, a polarization free EIT structure is shaped with the transmission peak showing up at 0.3 THz between the two drops at 0.27 THz and 0.42 THz. The filter design made up of two layers, first layer is formed by two opening aperture square rings made up of aluminum. The second layer is made up of crystal quartz.

Jin Huang and et.al [30] proposed a bandwidth controllable terahertz metamaterial bandpass filter using vanadium dioxide. The designed filter has the bandwidth of 0.32THz for no bias voltage. The bandwidth and passband frequency can be varied by applying variable bias voltage for various parts of metal patterns. Bandwidth increases by 0.13THz and decreases by 0.12THz. Passband frequency is varied by 0.12THz. Broadband THz passband filter is made up of metal-vanadium dioxide-dielectric-metal-vanadium dioxide (MVDMV). The Design consists of a Metal loop, Upper Vo2, polymide, metal split ring, lower Vo2.
Wei Wang and et.al [31] proposed the THz band-stop filter using graphene monolayers, the design uses electrical tuning. By changing the tuning voltage from 8.5V to 24.9V center frequency is varied from 6.6 to 8.6THz. The filter is independent of the divergence state of an incident wave because of high azimuthal equilibrium. The proposed filter is used in a gas detection sensor. The proposed structure uses polyimide substrate, over which two graphene monolayers are deposited and two layers are separated by Al₂O₃. Graphene layer optical property is varied by changing voltage V_g.

Haritha Mohan and et.al [32] proposed the THz bandstop filter on a complementary split-ring resonator (CSRR). The filter is made on a GaAs dielectric substrate with gold conducting layer on both the sides. The CSRR structure is made on the top conducting layer. At 0.3THz frequency the filter shows the low insertion loss of -33dB and the group delay of -0.03ns. The filter acts as notch filter at 0.3THz frequency. CSRR has GaAS dielectric substrate with Gold conducting surface on both sides, the split rings are imprinted out from the conducting surface. The gap between the two rings creates strong spread capacitance of CSRR.

P Demchenko and et.al [33] proposed THz Notch filter using Carbon Nanotubes (CNT) which are optically tunable. CNTs have a remarkable capability to absorb electromagnetic radiation in an wide spectral range. In a polyethylene terephthalate (PET) substrate Aluminum cross-shaped resonator is designed. The cross-cavity parameters like width W, period G, & length L are used to determine the resonant frequency. Designed Notch filter shows the resonant frequency of 0.15THz, the bandwidth of 0.02, and Quality factor 7.5.

Lujing Xing and et.al [34] proposed a parallel-plate waveguide-based Terahertz multichannel notch filter. The Resonance frequency is determined by the plate separation ‘b’, width ‘w’ of the channels. The progressive way of THz radiation through the four PPWG-based T-formed dumps discovers four resonance frequencies. The height of the T-formed dumps is h=1mm, the width of the dumps varies w₁= 0.3395, w₂= 0.343, w₃= 0.3465, w₄= 0.35 and b₁–b₄, are 0.97, 0.98, 0.99, and 1 mm. The design results show four resonance frequency at 297.1, 300.1, 303.2, and 306.3 GHz.

In this article, we proposed the concept of various THz filters based on Metamaterials, frequency selective surface, and Parallel plate waveguide. We also compared frequency selection and rejection capabilities of different materials and tunability of center frequency and bandwidth. Also, we proposed the SRR based terahertz bandpass filter.

### Table 1: Performance analysis of various THz bandpass filters

| S.No | Method                          | Material         | Resonant frequency(f_c) | Bandwidth | Advantages                                      |
|------|---------------------------------|------------------|-------------------------|-----------|-------------------------------------------------|
| 1    | Frequency selective surface (FSS)| Metal            | 1THz                    | 0.44THz   | Low insertion loss                              |
| 2    | Multilayer Metamaterial         | SiO₂, Gold       | Tunable                 | 1THz      | Wideband, Tunable, easy to construct.           |
| 3    | Parallel plate Waveguide        | Silver (Ag)      | Tunable                 |           | High Quality factor, high transmittivity.       |
| 4    | Double layer FSS                | Metal            | Tunable                 |           | High frequency selectivity, high roll-off rate, low insertion loss |
| 5    | Complementary metasurface       | Aluminium, Quartz| 0.405THz               |           | -                                               |
| 6    | Metamaterial                    | Vanadium dioxide | Tunable                 | 0.20-0.45THz | -                                               |
2. Proposed design of SRR based THz bandpass filter

In this Article, Split Ring Resonator (SRR) based terahertz bandpass filter is designed. Frequency selective surface (FSS) have a band stop or bandpass frequency response. SRR is patterned on a geometrically thin copper layer on a substrate. Only the signals around the center frequency can be passed through a split ring resonator. The copper layer is made as a perfect electric conductor, other domain in the unit cell is filled by air.

All four sides of the design is assumed as Floquet-periodic boundary condition. Top and the bottom layers of the unit cell are used as Perfect matched layers (PMLs). The PMLs is used to attenuate the perpendicular waves to the PML boundary. The PMLs wavelength is set to $2\pi/k_0\cos\theta$.

Internal boundaries of PMLs assigned with Port boundary conditions. Port boundary condition determines the transmission characteristics and reflection characteristics. The magnetic resonance is obtained by the gaps between the two rings and split width of ring. SRR behaves like a parallel LC resonating structure. Current flows along the ring and completes at the gap. Induced current passes from one ring to another through capacitor gaps in the form of displacement current.

The resonant frequency is given by

$$f_c = \frac{1}{2\pi\sqrt{L_0C_0}}$$

(1)

If the split width ‘d’ increases, the capacitance decreases which increases the resonant frequency. Gap distance ‘t’ increases, the mutual capacitance decreases which increases the resonant frequency. Metal width ‘w’ increases, mutual capacitance, and mutual inductance decreases which decreases resonant frequency.

3. Simulated Output and Discussions

Square shaped split-ring resonator structure is proposed here, it acts as a bandpass filter in the terahertz region. Three designs are investigated with the change in w, t, and d parameters. The results of the three designs are plotted for various values of d. The proposed design shows the high tunable center frequency and high bandwidth.

![Fig.1 a) Schematic of proposed SRR based bandpass filter with w=1.5µm, t=1.5µm and](image)
b) Transmittance plot for various d value.

![Schematic of proposed SRR based bandpass filter with w=1µm, t=1µm and b) Transmittance plot for various d value.](image)

![Transmittance plot for various d value.](image)

Fig.2 a) Schematic of proposed SRR based bandpass filter with w=1µm, t=1µm and b) Transmittance plot for various d value.

![Schematic of proposed SRR based bandpass filter with w=1µm, t=2µm and b) Transmittance plot for various d value.](image)

![Transmittance plot for various d value.](image)

Fig.3 a) Schematic of proposed SRR based bandpass filter with w=1µm, t=2µm and b) Transmittance plot for various d value.

The simulation is carried out by using COMSOL Multiphysics software, the resonant frequency and bandwidth are determined by split width ‘d’, gap distance ‘t’ and metal width ‘w’ of the split ring resonator, it shows that the increase in d, increases in resonant frequency and bandwidth. Design 1(Fig 1) shows the resonant frequency range from 3.6THz to 7.2THz and bandwidth ranges from 1.1THz to 3.4THz. Design 2(Fig 2) shows the resonant frequency range from 3.8THz to 7THz and bandwidth ranges from 0.9THz to 3.3THz. Design 3 (Fig 3) shows the resonant frequency range from 3.8THz to 6.8THz and bandwidth ranges from 1THz to 3.6THz.

4. Conclusion
In this article, we have investigated various terahertz filters based on metamaterials, frequency selective surfaces, and parallel plate waveguides. The comparison result shows the center frequency, bandwidth, and advantages of different bandpass filters. In this article, we also proposed SRR based Terahertz bandpass filter, which produces tunable center frequency (3.6THz to 7.2THz) and high bandwidth (0.9THz to 3.6THz) compared to other types of filters investigated above. The proposed design is easy to construct. The proposed bandpass filter is used in terahertz imaging and communication.

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