Enhancing the Selectivity of Frequency Selective Surfaces for Terahertz Sensing Applications

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Abstract—**This paper introduces a new technique for enhancing the selectivity (or the quality factor, *Q*-factor) of frequency selective surfaces (FSS) for sensing applications. The proposed FSS functions as a free-space bandpass resonator, designed to sense the changing dielectric properties of minute amount of materials loaded on the FSS. The *Q*-enhancement technique is mainly based on two concepts; enhancing the field concentration in a given area and introducing transmission zeros in the FSS response. Two designs based on a modified complementary split-ring resonator (CSRR) at 300 GHz have been proposed. The first one is composed of complementary triple-split ring resonators. The splits divided the structure into arcs of different lengths. As a result, the transmission zero is obtained in the passband due to a destructive coupling. This produces a resonance *Q*-factor of 41. By controlling the orientation of the three splits, higher *Q*-factor of 84 is attainable. The second structure is designed using concentric triple-split rings. The added electromagnetic coupling between the concentric rings makes the transmission response steeper as compared with the single triple-split ring, and the quality factor increases from 41 to 90. By reducing the inter-spacing distance by three times, the Q-factor can be further increased to 256. The parameter studies of the FSS structures based on full-wave simulations have been presented.**

Keywords— ***terahertz sensing; frequency selective surfaces; split-ring resonators; concentric split- ring resonators; Q-factor; transmission zeros***

I. INTRODUCTION

Innovative applications in terahertz (THz) frequency ranges have fascinated the world's interest. Many biochemical samples exhibit particular absorption coefficients and refraction index in terahertz frequency range. Therefore THz sensors can be used to identify their complex dielectric permittivity by examining the resonant frequency [1]. Resonance-based terahertz sensors have proved a high potential in detecting and identifying biochemical samples [2], [3]. Many different resonator techniques have been studied, such as frequency selective surfaces (FSS), microstrip lines, parallel-plate microcavities and attenuated total reflection (ATR) [4].

A FSS is a surface structure containing a two dimensional array of periodic cells of different geometries. They are designed to perform as filters, resonators, reflectors or beam splitters [5]. For sensing and material characterization [4], FSS is usually used as a free-space resonator. FSSs have been used in various sensing applications to detect single/double stranded DNA [9], proteins [6], liquid crystals [11] and earth's atmosphere [7]. Regarding bio-molecular sensing, split ring resonators with various configurations have been extensively discussed theoretically and experimentally [7], [8]. In order to detect minute amount of samples, it is highly desired for the FSS resonators to have high frequency selectivity (or high quality factor, *Q*-factor) so that the resonance curve is sufficiently sensitive to the small change of dielectric properties. It is also important to place the sample to a point of high electric-field concentration [9]. There are various ways to achieve this. By controlling the oblique incidence angle, the periodicity of the unit cell or the thickness of the FSS, the *Q*-factor of the FSS can be enhanced [5], [10]. Another method for reaching high *Q*-values is to introduce transmission (reflection) zeros in the pass (stop) band. Transmission (reflection) zeros can be generated from the cancellation effect of different transmission (reflection) paths [12]. It has been argued and demonstrated that the break of symmetry of the unit cell either geometrically or electromagnetically can produce transmission (reflection) zeros in the bandpass (bandstop) FSS [13]. In this paper, complementary triple-split ring and concentric triple split ring FSS resonators have been demonstrated to produce transmission zeros and high *Q*-factors in a bandpass scenario. It is worth mentioning that the FSSs in this paper are intended to be designed for fabrication using SU-8 micromachininig technique [10]. This technique enables freestanding FSSs without the need of dielectric substrates. The thickness of the structure can range from tens to hundreds of micrometers. So it is essentially a thick volumetric structure rather than a thin surface structure as for conventional FSSs. The thickness plays an important role [10]. In order to separate the intrinsic characteristics of the unit cell geometry from the thickness effect, thin FSS structures are first assumed and investigated in this paper. The effect of the thickness is discussed later in Section V.

II. COMPLEMENTARY SPLIT-RING RESONATORS

This section discusses the *Q*-factors of different known complementary split-ring resonator structures as a reference for the proposed new designs. They are a full ring slot (Fig. 1(a)), a

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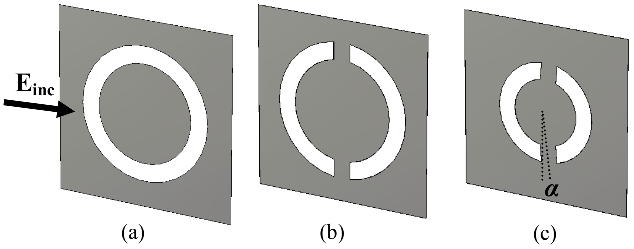
symmetric double-split ring slot (Fig. 1(b)) and an asymmetric double-split ring slot [3] (Fig. 1(c)). All the designs are simulated using CST Microwave Studio and are optimized to resonate at 300 GHz with the same slot width of 0.06 mm. The outer radii of the three designs are 0.230, 0.235 and 0.179 mm respectively. To simulate an infinite FSS structure, a unit cell with a periodic boundary condition is used. The complementary ring resonators in Fig. 1 are excited by the TM00 mode when the E-field polarization is horizontal. The loaded *Q*-factor Q_L is calculated from the 3-dB bandwidth as:

$$Q_L = f_0 / \Delta f_{-3dB} \tag{1}$$

The full and the symmetric double-split complementary ring resonator have the same quality factor of only 2. In contrast, the asymmetric double-split complementary ring resonator gives a quality factor of 88 (Fig. 2.). The asymmetric structure has a narrow 3dB bandwidth due to the appearance of a transmission zero. The null results from a destructive coupling when the incident wave passes through the two arcs of slightly different lengths [3]. This is also known as a result of “trapped mode” [13].



(a) (b) (c)

Fig. 1. (a) Full ring slot, (b) symmetric double-split ring slot and (c) asymmetric double-split ring slot, $\alpha = 5^\circ$.

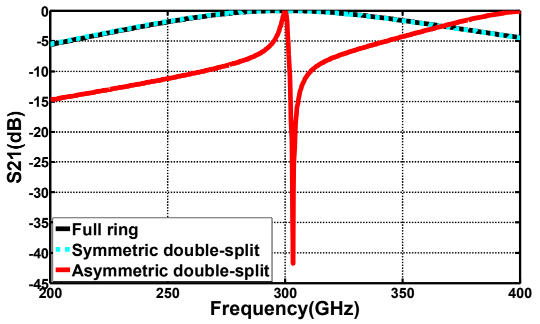


Fig. 2. Simulated transmission responses (S_{21}) of the three structures in Fig. 1.

III. PROPOSED DESIGNS

A. Complementary Triple-Split Ring Resonator

It should be noted that when the E-field is vertically polarized, the symmetric double-split ring slot in Fig. 1(b) does not exhibit the resonant characteristic due to its symmetry. The two symmetric short-circuit points in the ring slot suppress the half-wavelength resonance. By introducing a third short-circuit point in the ring slot as shown in Fig. 3, half-wavelength resonances can be established in the two longer arcs even with a vertically polarized E-field excitation (TE mode). Enhanced transmission occurs as a resonance peak. Fig. 3 shows the proposed complementary triple-split ring resonator (C-TSRR). A transmission zero is obtained above the resonance as shown in Fig. 4.

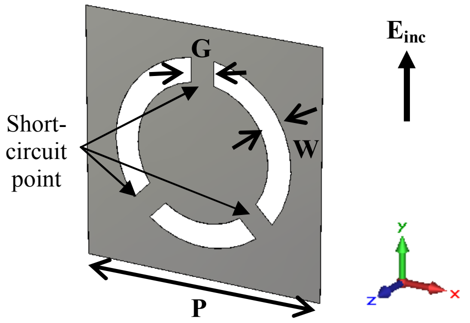
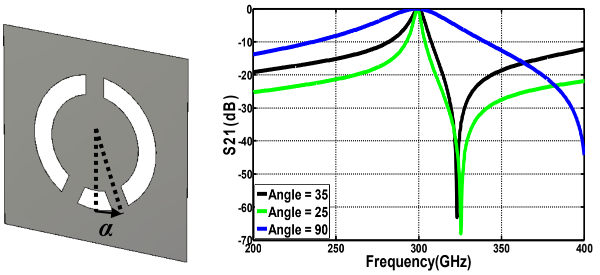


Fig. 3. Complementary triple-split ring resonator.

The main parameters of the C-TSRR are the periodicity P = 0.625 mm, slot width W = 0.06 mm and the width of the short-circuit point G = 0.06 mm. The outer radius of the ring is adjusted to 0.233 mm to resonate at 300 GHz. The plane wave excitation (TE00 mode) propagates normal to the XY plane, the electric field is in the Y-direction and the magnetic field is in the X-direction. Fig. 4 shows the transmission response with a loaded Q = 41. The transmission zero appears at 323 GHz while a second one appears at 454 GHz. With a TM mode excitation (horizontal E-field), the Q-factor of the C-TSRR is significantly lower.

The C-TSRR resonance is sensitive to the length of the lower arc, or the offset angle α of the two lower short-circuit points. As shown in Fig. 4, when the offset angle α is 90°, the Q-factor was as low as 8.5. As the offset angle decreases, the transmission spectral becomes steeper and the Q-factor increases to 84 when $\alpha = 25^\circ$.



(a) (b)

Fig. 4. (a) Complementary triple-split ring resonator with the offset angle α, (b) Transmission spectrum when the offset angle is 90°, 35° and 25°.

B. Complementary Triple-Split Concentric Ring Resonator

The concentric triple-split complementary ring resonator (C-TSCRR) shown in Fig. 5 consists of two concentric ring slots with three short-circuit points each. The previously described characteristics in C-TSRR are also revealed in this

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structure. In addition, the effect of electromagnetic coupling between the concentric slots enhances the Q-factor further.

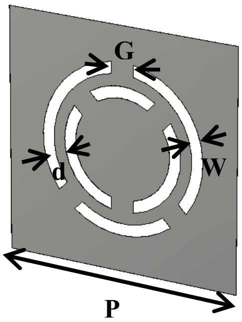


Fig. 5. Complementary triple-split concentric ring resonator. P = 0.625 mm, G = 0.06 mm, W = 0.03 mm.

As the second ring is added to the resonator, mutual inductive coupling between the two ring slots takes place. The outer radius of the slot is adjusted to 0.215 mm to resonator at 300 GHz. The energy stored within the FSS increases and the Q-factor increases. The transmission responses of the C-TSCRR and C-TSRR with the same offset angle of 35° are compared in Fig. 6. The C-TSCRR structure resonates at 299.4 GHz with a reflection coefficient of -57 dB and a transmission zero at 310 GHz. The simulated loaded quality factor is 90 as compared with 41 in the case of C-TSRR. The split of the inner ring slot is beneficial. With a full inner ring slot, the resonance from the full inner ring is closer to the main resonance peak and the Q-factor is lowered to 48.

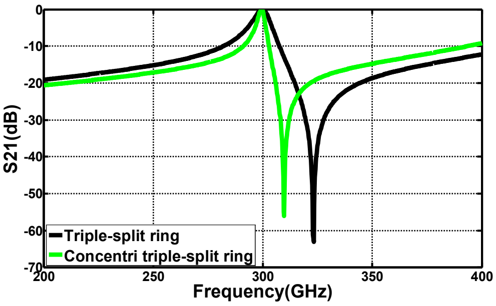


Fig. 6. Simulated Transmission (S_{21}) responses of the concentric triple-split ring FSS structures.

IV. DISCUSSION

The transmission response of the C-TSRR FSS has been analyzed using simulated field distributions. The TE mode excitation has a vertical polarization of the electric field. Fig. 7 shows the simulated current distributions at the transmission peak and zero respectively. At 300 GHz, the upper pair of arcs clearly exhibit a half wavelength resonance with the current maxima at the short-circuit points and minima above the horizontal center. For a symmetric double-split ring slot, such a half wavelength resonance will be suppressed as there would be no residual E-field in the vertical direction. At $f = 323$ GHz as in Fig. 7(b), first it should be noted that the current magnitude is much lower as indicated by the different scales. Although it is not quantified, it is believed the vertical E-field residue from the upper arcs is cancelled out due to the increased coupling between the upper pair through the lower arc.

For the concentric triple-split complementary ring structure, from Fig. 8, it is observed that when decreasing the inter-spacing between the two rings, the transmission zero shifts closer to the transmission peak. This increases the Q-factor. By reducing the inter-spacing distance d from 0.03 mm to 0.01 mm, the FSS Q-factor is increased from 90 to 256.

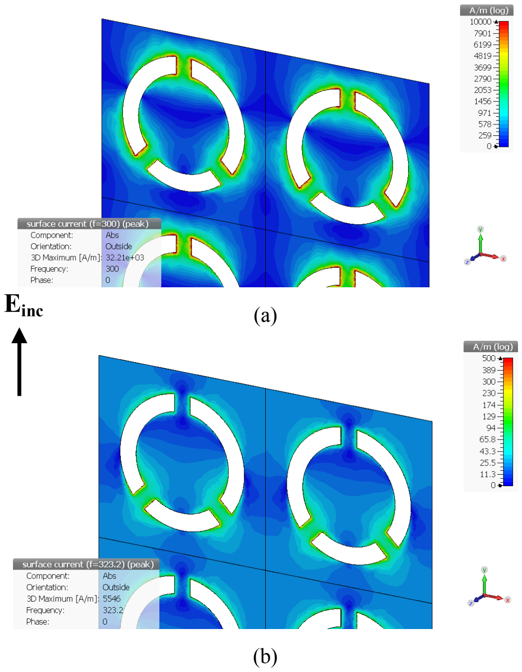


Fig. 7. Surface current distribution of the C-TSRR at (a) $f = 300$ GHz (Transmission peak) (b) $f = 323$ GHz (Transmission zero). Note the scale is 10000 A/m in (a) and 500 A/m in (b).

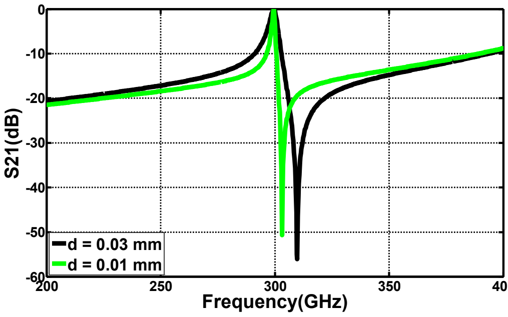


Fig. 8. Simulated Transmission (S_{21}) response of the C-TSCRR FSS structure with different inter-spacing distance.

V. THICKNESS EFFECT

The thickness of the FSS structure affects the transmission response. It has been shown that when the thickness increases, more fields are concentrated in the guided region in the slots so more energy is stored within the structure. This will enhance the selectivity (*Q*-factor) of the frequency selective surface [10]. The effect of the thickness of the complementary triple-split ring resonator has been investigated. As shown in Fig. 9, as the thickness increases, the resonance frequency shifts upward. It is also observed that while the *Q*-factor increases with the thickness, the transmission zero frequency is pushed away from the resonance.

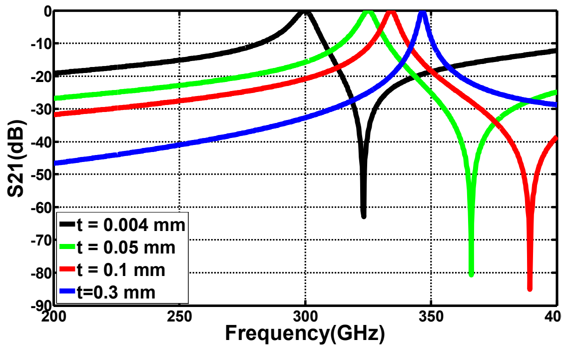
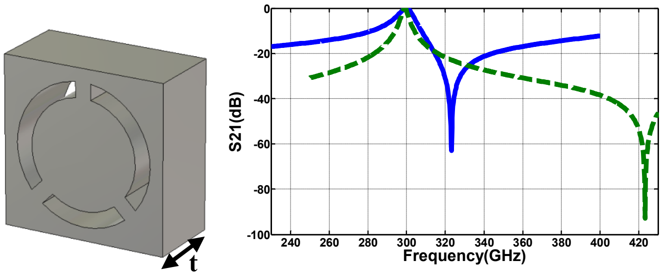


Fig. 9. Simulated transmission (S_{21}) response of the complementary triple-split ring resonator FSS structure with different thickness t = 0.004, 0.05, 0.1, and 0.3 mm.



(a) (b)

Fig. 10. (a) A thick complementary triple-split ring resonator. (b) Simulated transmission response (S21) of the complementary triple-split ring resonator with t = 0.004 mm (solid line) and t = 0.3 mm (dashed line).

As indicated in Fig. 10, when the thickness of C-TSRR structures is increased from 0.0004 mm to 0.3 mm, the quality factor is enhanced by 141% and the transmission zero is shifted upwards from the resonance frequency by 30%.

V. CONCLUSION

This work presented and analyzed several frequency selective surface structures to perform as resonators at terahertz range. Enhancing the selectivity of the FSS structure was the main contribution of this paper. This has been achieved by implementing transmission zeros through the introduction of triple short-circuit points in the ring slot structure (C-TSRR) and the coupling between concentric ring slots (C-TSCRR). Parameter studies have shown that controlling the offset angle of the lower pair of short-circuit points increases the quality factor significantly by at least 102%. The concentric ring structure can enhance the *Q*-value further due to coupling. The triple-split ring structure has the advantage of many design flexibilities and degrees of freedom. A combined manipulation of the geometric asymmetry and electromagnetic coupling has the high potential to enhance the selectivity of the FSS further.

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