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doi:10.15199/48.2022.08.14

Bandpass THz Frequency Selective Surface with Flat Passband

***Abstract**. The thickness of the substrate turns out to be approximately a quarter of a wavelength in implementing second-order passband frequency selective surfaces (FSSs) to achieve better response with faster roll-off and smooth in-band frequency response. The problem with using a thicker substrate in FSS structures is that the losses will be high, especially in millimeter and terahertz (THz) frequency applications. For that, a new approach is introduced in this paper to deal with this issue. The approach is to adopt an improvement of the coupling coefficient without increasing the thickness of the substrate. Based on this, a thin band-pass filter (FSS) with low losses and flat-top response is built. An equivalent circuit model has been provided to characterize the structure based on electric and magnetic fields distributions. Thus, it is proven in this paper that the calculated results are in good agreement with the numerical simulation results.*

Streszczenie.** Okazuje się, że grubość podłoża wynosi około jednej czwartej długości fali w implementacji powierzchni selektywnych częstotliwościowo pasma przepustowego (FSS) drugiego rzędu, aby uzyskać lepszą odpowiedź z szybszym wycofywaniem się i gładką odpowiedzią częstotliwościową w paśmie. Problem z użyciem grubszego podłoża w strukturach FSS polega na tym, że straty będą wysokie, szczególnie w zastosowaniach o częstotliwościach milimetrowych i terahercowych (THz). W tym celu w niniejszym opracowaniu wprowadzono nowe podejście do rozwiązania tego problemu. Podejście polega na przyjęciu poprawy współczynnika sprzężenia bez zwiększania grubości podłoża. Na tej podstawie budowany jest cienki filtr pasmowoprzepustowy (FSS) o niskich stratach i płaskiej odpowiedzi. Dostarczono równoważny model obwodu w celu scharakteryzowania struktury w oparciu o rozkłady pól elektrycznych i magnetycznych. Tym samym dowiedziono w niniejszej pracy, że obliczone wyniki są w dobrej zgodności z wynikami symulacji numerycznej.* (Powierzchnia selektywna pasma przepustowego THz z płaskim pasmem przepustowym***)

Keywords: THz, FSS, filter, flat passband.
Słowa kluczowe: powierzchnia selektywna, pasmo THz.

Introduction

The band of frequencies between the millimeter and infrared frequencies is called the THz band, which is the region of the electromagnetic spectrum in the range of 100 GHz (3 mm) to 10 THz (30 μm).

In the last few years, THz-system has been launched as a bright wireless technology. Typical applications of THz-systems are security scanning, spectroscopy, high speed wireless-communication, in detection of impurities in pharmaceutical industry, and medical visualization due to terahertz radiation can penetrate plastics and fabrics, [1-2]. The THz frequency selective surface (FSS) could be realized by printing metal elements on the front side or on both sides of a dielectric [3-4]. Generally speaking, the response characteristic of a THz FSS is determined by the metal surface shape of the array element, the conductivity of the surface, permittivity of the substrate, and wave angle of incidence. Metal grid-shaped and related shapes have been depicted that they are appropriate elements to construct THz FSSs. The THz FSS can be represented by its equivalent circuit which is important to study THz FSS characteristics [5-9].

In general, several FSS structures have been designed in millimeter and sub-millimeter bands [10-14]. Instance for wideband FSS structures, Second order FSS structure by using complementary surfaces [15], crossed-dipole [16], Jerusalem-cross [17], ring-shaped [18], semi-circle [19], double square-loop, and gridded double square-loop [20].

Traditionally, the procedure used to design millimeter and terahertz FSSs with a flat-top and quick roll-off frequency response is by cascading elements [21]. For each element of the FSS structure, the surfaces act as resonators and are separated by insulating layers (a dielectric substrate). One practical issue of designing the flat top and fast roll-off response band-pass FSS is that the substrate is thick (around a quarter of the wavelength) [22]. Generally, thinner substrates are better for minimizing radiation loss [23]. The thick substrate will increase the losses because most of the losses in the THz FSS come from the transmission line (dielectric media). However, increasing the permittivity can decrease the bandwidth and shift the resonance frequency of the FSS backward. While decreasing the substrate thickness can decrease the bandwidth and shift the resonance frequency forward.

In the proposed structure, the desired response is achieved with a thinner substrate. The proposed structure is a second-order band-pass FSS, where the surfaces represent the resonators. The two surfaces are coupled by an inductive layer to reduce the ripples in passband response. The dimensions (length × width) of the proposed FSS element are 0.22λ×0.22λ and the overall thickness is less than λ/19 at the lower resonant frequency (208 GHz). This is significantly thinner than the thickness of FSSs with flat-top passband response designed using traditional approaches.

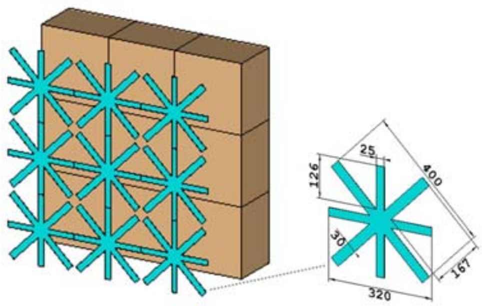


Fig. 1. Schematic diagram of the single-layer FSS with 3×3 elements, units in μm.

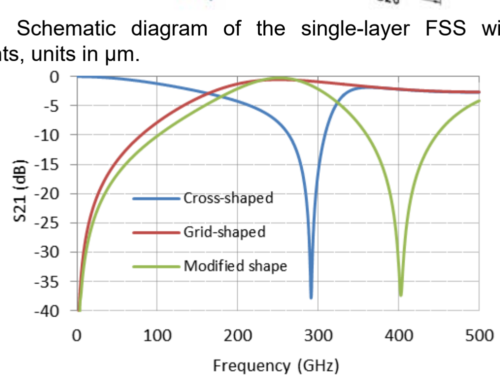


Fig. 2. Transmission coefficient of the FSS (single-layer) structure.

Filter design and simulation

It is well-known that the classical grid-shaped FSS works as a band-pass microwave filter, while the classical cross-shaped FSS works as a band-stop microwave filter. This can be explained by using the equivalents circuit of these structures. The equivalent circuit of the classical grid FSS is a parallel of an inductor with a capacitor (*LC*), while the equivalent circuit of the cross-shaped FSS is a series of an inductor with a capacitor (*LC*) [5]. As mentioned, this work aims to design a flat-top and fast roll-off response with a simple configuration. A design with such specifications may require the integration of a band-pass filter with another band-stop filter. Therefore, in the proposed THz FSS, the cross-shaped and the grid-shaped are combined into one element, at an angle of 45o between them, to obtain the desired response as can be seen in Fig. 1. The responses of the classical shapes and proposed structure are depicted in Fig. 2. The proposed structure response has a sharp transition edge at a high band.

Designing band-pass FSS with a flat top and fast roll-off requires exciting more than one resonant frequency and coupling them together. For that, two surfaces of the proposed structure are cascaded, and separated by a dielectric substrate as depicted in Fig. 3. The surfaces are made of copper with a 0.15 μm thick. The element dimensions (length × width) are 320 μm × 320 μm, the strip width is 25μm. The substrate is PEN with a 2.95 relative permittivity [24] and 230 μm thick. The FSS is intended to pass the band 159 GHz to 245 GHz.

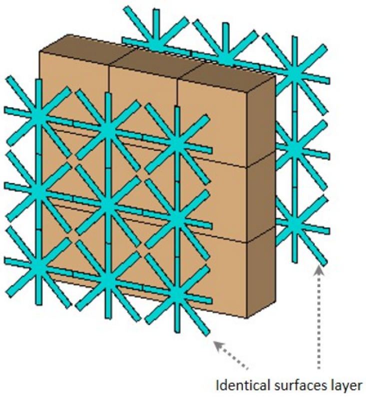


Fig. 3. Schematic diagram of the FSS (two-layer) with 3×3 elements

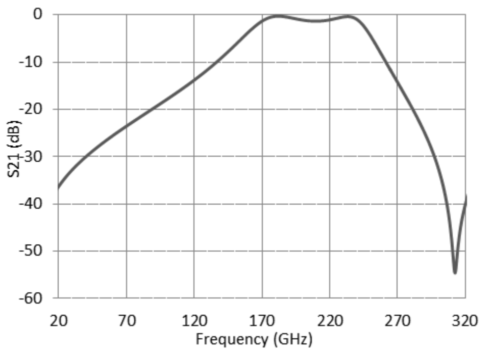


Fig. 4. Transmission coefficient of the FSS (two-layer) structure.

The THz band-pass filter is simulated and the result is depicted in Fig. 4. The designed FSS displays high performances, characterized by the top-flat and fast roll-off passband response with the fraction bandwidth (FBW) of 54% at the lower resonance frequency. However, the losses in the passband response can be as high as 1.3 dB and come from the substrate and metal of the structure.

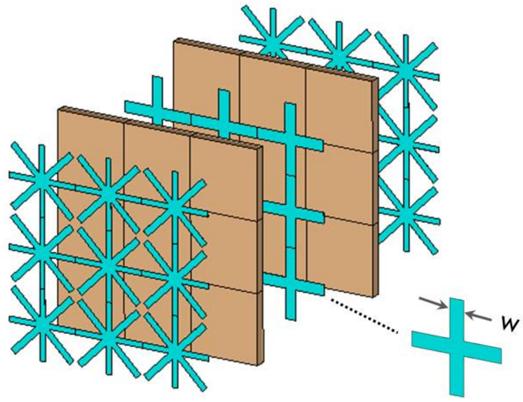
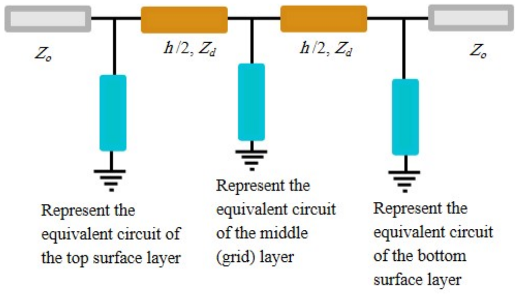
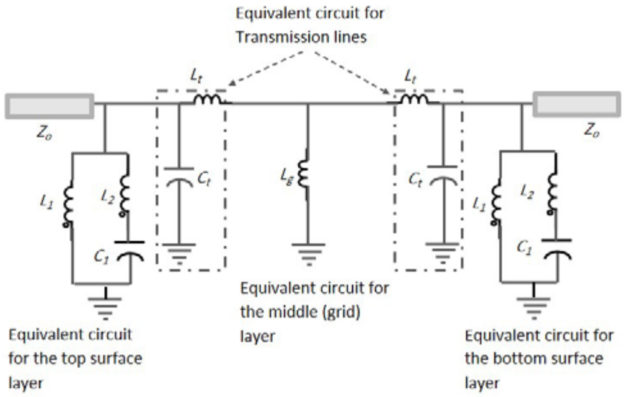


Fig. 5. Topology of the proposed flat-top response bandpass THz FSS.

a)



b)



c)

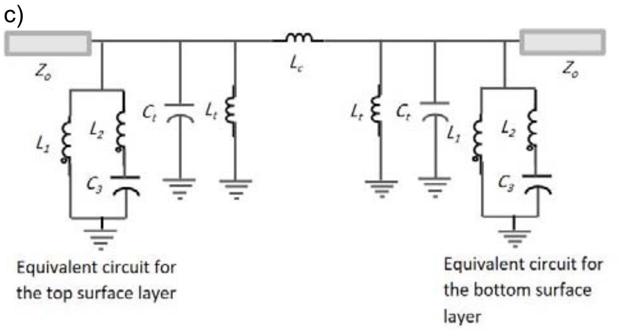


Fig. 6. Equivalent circuit model of the modified THz FSS, (a) with transmission lines, (b) series inductors and shunt capacitors instead of transmission lines, (c) after the star-delta transformation.

Reducing ripples and losses in passband response

This section will focus on reducing ripples in passband response and substrate thickness, and describe in detail the approach used to improve performance. The structure with same dimensions illustrate above will be modified to exhibit a flat-top and fast roll-off frequency response with losses as low as possible. The substrate separating the surfaces (resonators) and can be represented by a short segment of a transmission line. The equivalent circuit of the segment of line is a series inductor (L_t) and a shunt capacitor (C_t). One way to reduce the passband response ripples is to improve the coupling coefficient of the resonators. Traditionally, coupling between resonators can be improved by increasing the thickness of the substrate, but the disadvantage of using such a technique will increase the losses in transmitted power especially in high-frequency applications. Moreover, the structure will be bulky and unfavorable in some applications. A new approach is introduced to overcome these problems by adding an inductive layer in the middle of the structure, as shown in Fig. 5. In order to better understand the approach, a simple equivalent circuit is considered to represent the proposed FSS as depicted in Fig. 6, which is suitable for normal incidence. The equivalent circuit of the surface layer (resonator) is a parallel inductor (L_1) with a series of (L_2C_1), while (L_g) represents the middle metal layer (grid layer) as depicted in Fig. 6(b). The dielectric slabs separating these surfaces are represented by two identical short transmission lines with a characteristic impedance of (Z_d /2) and length of (h/2) for each, where $z_d = z_0/\sqrt{\varepsilon_r}$, εr is the relative permittivity of the substrate and Zo is the free space impedance. The three inductors of transmission lines and grid layer (star connection), as can be observed from Fig. 6(b), can be changed to the delta connection as depicted in Fig. 6(c) utilizing the well-known star-delta transform [25]. Assuming that each resonator (surface) is coupled only with the resonator adjacent to it. The coupled inductor between the surfaces can be calculated as:

(1) $$L_c = 2L_t + L_t^2/(L_g)$$

where Lc acts as the coupled inductor, and its value depends on the Lt and Lg as can be observed from equation (1). This means that the value of Lc has increased by the amount of $L_t^2/(4L_g)$ for the modified design compared to the case when no grid layer has been added in the middle of the structure. However, the value of Lg is controlled by the width of the grid strip (w), where it is inversely proportional to w. For the Parameters study, simulation with different values of grid strip width (w) has been carried out. The simulated result is depicted in Fig. 7, and there is an improvement in the response performance as the ripples are reduced in the passband region at a grid strip width of 60 mm. the substrate thickness is only 75μm (λ/19). This is agreed with equation (1), the increase in the grid strip width means that the value of the equivalent inductor of the grid layer (L_g) has decreased and this leads to an increase in the coupled inductor (L_c).

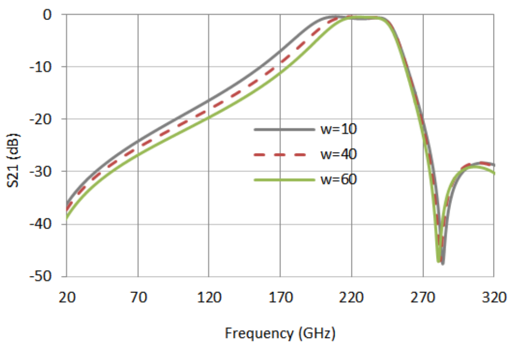


Fig. 7. Simulated transmission response of the proposed FSS with adding inductive layer.

Conclusion

A novel approach for designing low-profile and reducing the ripples in the passband response of second-order FSS is introduced. The approach is based on adding an inductive layer in between the resonators of FSS rather than increasing the thickness of the substrate to improve frequency response performance. As a result, a new THz bandpass (FSS) has a flat response is designed. The proposed structure can be considered as one of the thinner second-order bandpass FSS structure with low losses in passband response. The dimensions (Width × Length) of the designed structure are 0.23λ × 0.23λ and thickness of λ/9. Since substrate losses comprise most of the FSS losses, designing low-profile FSS as the described one in FSS will be very important for millimeter and THz applications

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