Design of Locally Deformed Flexible Frequency Selective Surfaces

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***Abstract*—A one-layer frequency selective surface (FSS) is proposed for filtering applications. The initial structure consists of one square ring on one side of the supporting dielectric layer. By performing cylindrical bending on the initial structure, the stopband can be shifted, or multiple stopbands can be obtained. Parametric analyses of the frequency response as a function of substrate thickness and structure width are reported, demonstrating the flexibility of the design by allowing for the potential of modifying the stopbands. The analysis has been carried out by full-wave electromagnetic simulation in the sub-10 GHz frequency range.**

I. INTRODUCTION

Due to their use as reflectors, selective absorbers, and spatial filters, frequency selective surfaces (FSSs) have drawn a lot of interest from the engineering industry [1, 2]. In recent years, cutting-edge solutions have been discussed, including flexible [3] and switched [4]. Such solutions are utilized in a variety of applications, including planar metamaterials, absorbers, radomes, filters, polarizers, and antennas [5]. The metallic components of the FSS often rely upon dipoles, hybrid loops/rings, square loops, circular rings, and fractal designs [5].

For example, a switchable FSS based on modified Jerusalem-cross geometry has been published [6]. It is possible to provide single and dual pass bands around the 2.45 GHz and 5 GHz bands by choosing the proper switch combinations. For various applications where bending properties are required, flexible substrates have been examined [7]. Also, a switchable frequency selective surface built on a flexible composite substrate is examined under various bending scenarios regarding bending curvatures and bending directions [5].

The current research starts from a classic structure with a final design objective of filtering in the Wi-Fi, Bluetooth and C bands, which are widely used in the automotive sector. A one-sided flexible FSS conceived for multi wide-band filtering applications is reported. A commercial solution is used to evaluate the filtering characteristics [8]. The design of the unit cell relies on one square ring and is built on an FR4 substrate. The cylindrical bending of the unit cells metal pattern required to achieve the targeted transmission qualities is presented step-by-step. The thickness of the substrate and the structure width is studied parametrically to show the possibility of changing the position of the stopbands.

The paper is organized as follows. In the next section, the design of the initial rigid FSS is presented and its filtering properties are assessed. In Section III, it is shown how the resonances of the surface can be combined by bending the initial structure at various angles. Section IV reports parametrical studies performed to control the stopband. The last section is dedicated to conclusions.

II. PROPOSED INITIAL STRUCTURE

The single square ring previously considered in [2] and shown in Fig. 1, serves as the basis for the design of the proposed FSS unit cell. The copper square ring is etched on one side of an FR4 substrate, (ε_r=4.3, tan δ=0.025). The dimensions are as follows: dimensions of the unit cell (along the coordinate axes x and y): d_x=d_y=15 mm, substrate thickness h=0.2 mm, trace width w of 0.4 mm (reduced from 0.5 mm in [2]) and the external edge of the metallic ring l is 14.9 mm (in comparison with 14.8 mm from [2]). The unit cell is repeated in 2D in the d_x and d_y directions to create the FSS. The value for the substrate thickness has been chosen aiming to allow experimental validation of the flexible structure in the future.

First, using [8], the transmission coefficient of the structure with a single simple square ring on only one side of the substrate was evaluated. A similar structure resonates at a single notch frequency that is determined by the square rings area [1, 2]. The amplitude of the transmission coefficient S_{21} of a plane wave that is linearly polarized and is normally incident is depicted in Fig. 2 (TE incidence). In this scenario, a 10 dB stop-band in the range (1.47 – 2.88 GHz) has been achieved (Fig. 2) with a bandwidth of 1.41 GHz yielding a single notch frequency (2.07 GHz), which contains the Wi-Fi and Bluetooth bands.

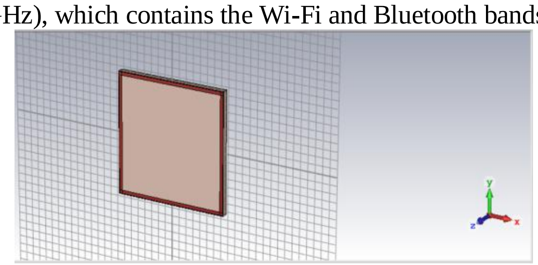

Figure 1. Unit cell geometry (initial structure).

The result in TM incidence (for the normal incidence case) is similar, due to the symmetry of the unit cell. For comparison, in the previous design [2], the notch was centered at 2.1 GHz with a 10dB stopband between (1.43 – 2.89 GHz).

A parametric investigation on the structure in Fig. 1 has been carried out to evaluate the sensitivity with respect to the angle of incidence of the electromagnetic plane wave. Only the modification of the transmission coefficient with the colatitude angle has been taken into account due to the symmetry of the structure.

Results of the parametric change of theta (colatitude angle) are depicted in Fig. 3. This parameter has been changed in five steps, from 0 to 60 degrees. In TE mode, the notch frequency is consistent up to 60º (the center frequency varies between 2.07 GHz and 2.20 GHz).

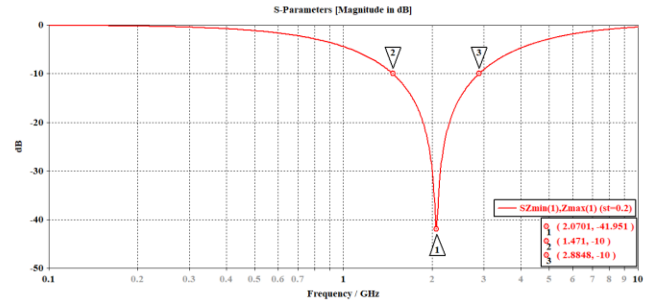

Figure 2. Result for the geometry in Fig. 1.

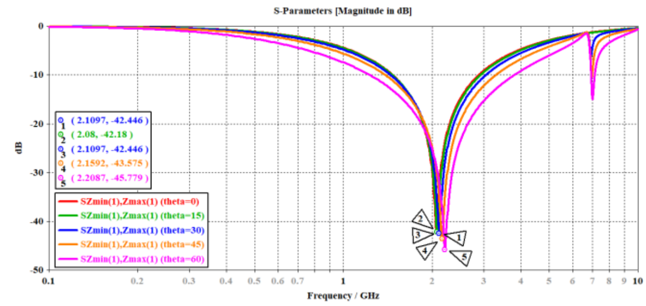

Figure 3. Transmission coefficient behavior for different incident angle (theta) for the structure in Fig. 1.

III. STRUCTURE BENDING

A. Positive angle structure bending

In order to design flexible frequency selective surfaces, cylindrical bending was applied to the structure and to the substrate in Fig. 1. At the beginning, a positive angle bending was investigated in this section, around the axis above the metallization. Firstly, we started with a bending angle of 45º, which is visible in Fig. 4 (a). Fig. 5 reports a 3 x 3 units cell region of the infinitely extended bent structure with set periodic boundary conditions.

The transmittance result for this bending is visible in Fig. 6. In normal incidence (TE case), the notch is centered at 4.90 GHz (within the frequency C band). TM case shows very similar results, so in the following results our study will be focused on TE case.

A theta parameter variation (between 0 and 60º, with a step of 15º) has been performed also in this case. One can notice that this structure is again insensitive to angular variation of the incidence (the notch central frequency varies slightly between 4.90 and 4.97 GHz, if we vary theta angle). Also, the cut-off varies between -48.00 dB and -50.24 dB.

Secondly, in Fig. 4 (b), a bending angle of 90º was performed on the structure in Fig. 1. The same investigation was performed, like for the previous bending: namely variation of theta angle, which is reported in Fig. 7.

In normal incidence (theta angle being 0), the notch is centered at 5.01 GHz this time, and it goes up to 5.05 GHz if theta is varied up to 60º. Now, the cut-off transmittance varies between -48.42 dB and -49.79 dB.

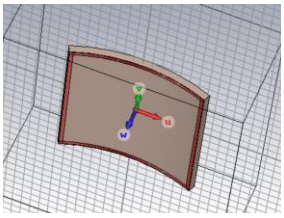

Figure 4 (a). Bending of the structure from Fig. 1 (45 º).

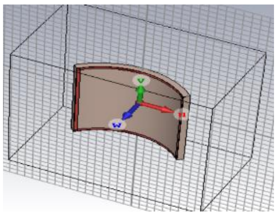

Figure 4 (b). Bending of the structure from Fig. 1 (90 º).

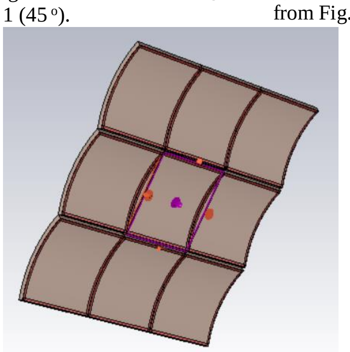

Figure 5. Infinitely extended bent structure.

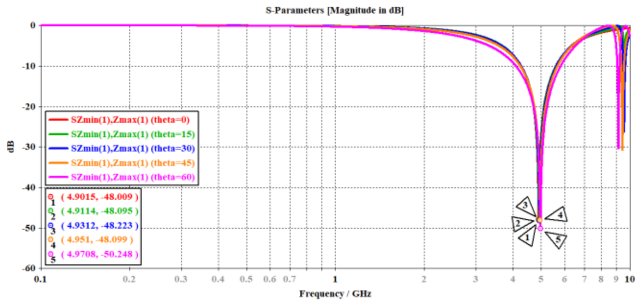

Figure 6. Transmittance result for the structure from Fig. 4 (a).

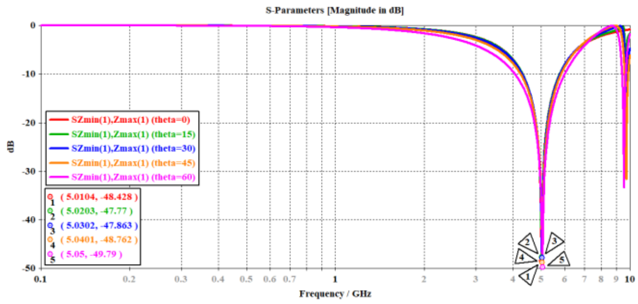

Figure 7. Transmittance result for the structure from Fig. 4 (b).

The final part of this section presents a comparison for transmittance in normal incidence, for various positive bending angles: initial structure (from Fig. 1), bending 45º (Fig. 4 (a)) and bending 90 º (Fig. 4 (b)).

In Fig. 8 one can observe the following: by means of cylindrical bending, the notch is moved to higher frequencies from 2.07 GHz (no bending) to 4.90 GHz (bending 45°) and 5.01 GHz (bending 90°) respectively. This is consistent with the decrease of the effective area of the square ring intercepted by the incoming wave as a result of the bending. Also, the cut-off varies, from -41.95 dB (no bending) to -48.18 dB (bending 45°) and -48.51 dB (bending 90°).

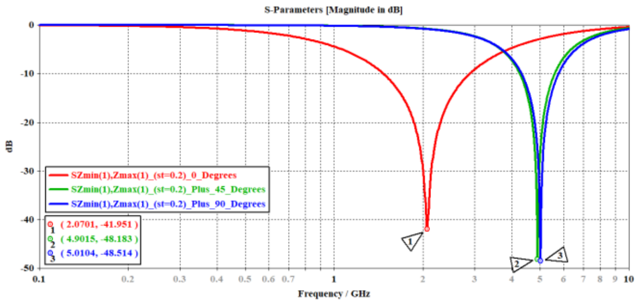

Figure 8. Comparison between transmittance for various bending angles.

B. *Negative angle structure bending*

In the following section we tackled the negative angle bending (oppositely with respect to the previous case), and started with a bending angle of -45°, which is visible in Fig. 9 (a).

The transmittance result for this bending is visible in Fig. 10. In normal incidence, the notch is centered at 4.65 GHz (again containing the C frequency band). A theta parameter variation (between 0 and 60°, with a step of 15°) has been performed for this case too.

It is visible that this structure is again insensitive to theta variation (the notch central frequency varies slightly between 4.65 and 4.94 GHz, if we vary theta angle). Also, the cut-off transmittance varies between -46.52 dB and -47.45 dB.

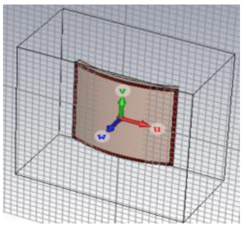

Figure 9 (a). Bending of the structure from Fig. 1 (-45 °).

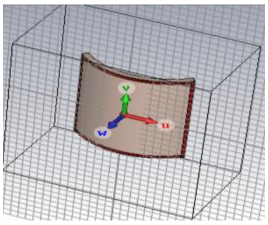

Figure 6 (b). Bending of the structure from Fig. 1 (-90 °).

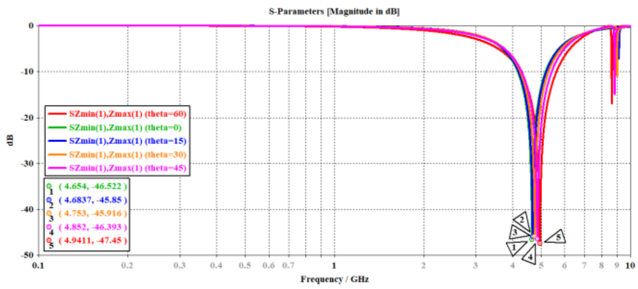

Figure 10. Transmittance result for the structure from Fig. 9 (a).

Next, in Fig. 9 (b), a bending angle of -90°, was suggested for the structure from Fig. 1. The same investigation was chosen, like for the previous bending: namely variation of theta angle, which is reported in Fig. 11.

In normal incidence (theta angle being 0), the notch is centered at 4.90 GHz this time, and it goes up to 4.97 GHz if theta is increased up to 60°. Now, the cut-off transmittance varies between -47.66 dB and -50.73 dB.

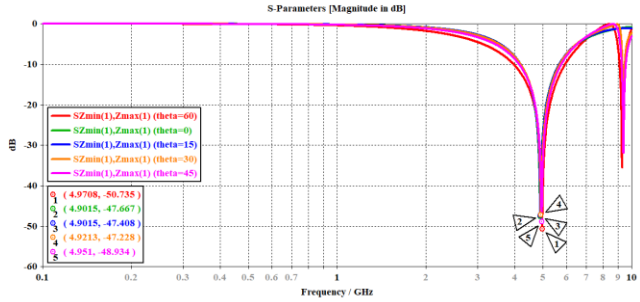

Figure 11. Transmittance result for the structure from Fig. 9 (b).

The final part of this section presents again a comparison for transmittance in normal incidence, but this time for various negative bending angles: initial structure (from Fig. 1), bending -45° (Fig. 9 (a)) and bending -90 ° (Fig. 9 (b)).

Observing the data in Fig. 12, the following conclusions can be drawn: by means of cylindrical bending, the notch is moved to higher frequencies from 2.07 GHz (no bending) to 4.84 GHz (bending -45°) and 4.90 GHz (bending -90°) respectively, due to the decrease of the effective area of the ring. Also, the cut-off transmittance varies, from -41.95 dB (no bending) to -48.41 dB (bending -45°) and -47.97 dB (bending -90°). Again, the negative bending of 45° and 90° depict a relatively similar result.

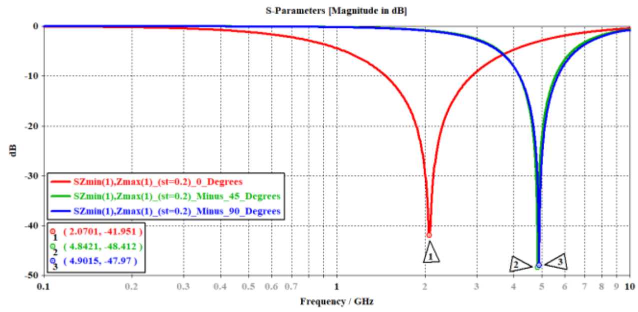

Figure 12. Comparison between transmittance for various bending angles.

IV. PARAMETRIC STUDIES

An investigation into the structure substrate thickness was presented on the design of the unit cell described above. The structure was firstly bent by 90**°** and secondly a -45**°** cylindrical bend has been applied to get the results. The following values were used to study this parameter: 0.2 mm, 0.8 mm, 1.6 mm, 2.4 mm and 3.2 mm.

As seen in Fig. 13, the stopband by using substrate thickness between 0.8 mm and 3.2 mm is centered on closely situated frequencies, with values between 4.69 GHz and 4.60 GHz, at a 90**°** bending of the structure. Only if a thickness of 0.2 mm is used, the results indicate that the thickness of the structure does significantly affect the frequency at which the stopband is centered (5.01 GHz). when the structure is bent in a positive direction

In the second instance (Fig. 14), the structure was bent at a

-45º angle and it was found that there was a sizable variation in the stopband center, with measured values spanning between 4.65 GHz and 3.72 GHz.

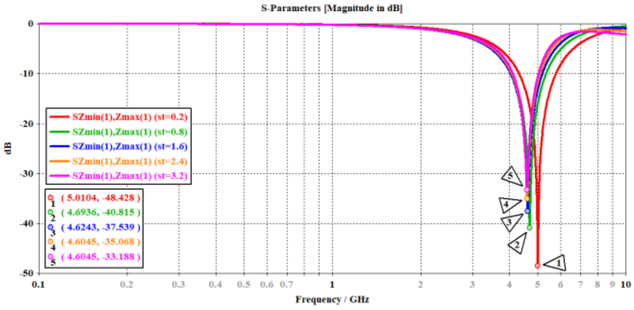

Figure 13. Substrate thickness variation for 90 º bending.

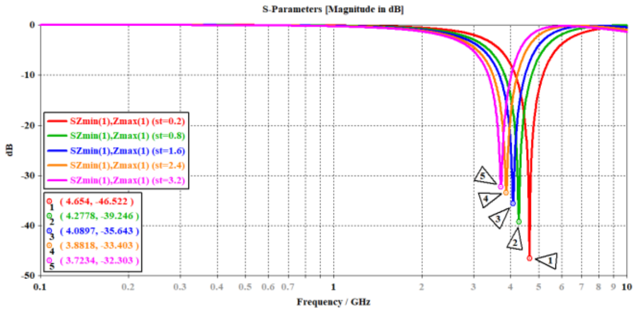

Figure 14. Substrate thickness variation for -45 º bending.

The second study aimed to elucidate the impact of the modification of the trace width of the structure at various bending angles, starting with a trace width of 0.2 mm and going up to 1 mm. In Fig. 15, one can see the results when the original structure was bent at an angle of -45º. The stopband was between 4.16 GHz and 5.16 GHz with a notch centered on 4.65 GHz and a cut of -46.522 dB at the start value of the trace, 0.4 mm.

Two notches are present at 0.2 mm trace width, the first at 1.74 GHz and the second centered at 5.03 GHz. The following measured value was at a trace width of 0.6 mm using a simulation step of 0.2 mm. In this instance, there were also two notches, the centers of which were at 2.22 GHz and 5.65 GHz, respectively.

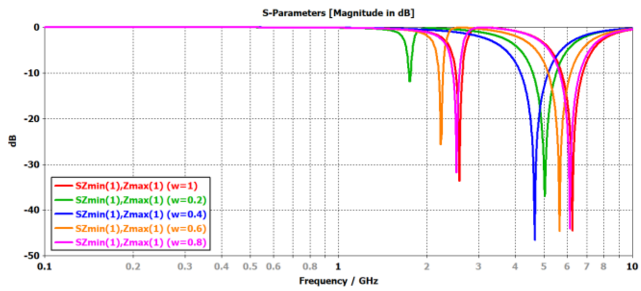

Figure 15. Width variation for -45 º bending.

The first stop band was centered at 2.51 GHz and the second one at 6.12 GHz when the trace width reached 0.8 mm. The latest study used a 1 mm trace width, and like the others, it discovered two notches at 2.57 GHz and 6.24 GHz.

When the structure was bent at an angle of 90º, the results were more frequency-dependent than in the other example, with values at 0.4 mm forming a stop band between 4.32 GHz and 5.77 GHz and a notch at 5.01 GHz with a -48.428 dB cut-off transmittance (this result will reported be at the paper presentation).

Two stop-bands, the first of which is centered at 2.86 GHz and the second of which is centered at 7.90 GHz, can be seen at a trace width of 0.2 mm. The first stop-band center frequency was 2.65 GHz, and for the second stop-band was at 6.61 GHz, when the trace width achieves a value of 0.8 mm. The most recent analysis at 1 mm revealed two additional stop-bands with centers at 2.75 GHz and 6.79 GHz.

V. CONCLUSIONS

This article proposed an FSSs with unit cells made of a metal pattern based on a square ring on one side of the substrate, built on FR4 material. Flexible structures have been considered by means of cylindrical bending in order to tune the stop bands. The proposed FSSs potential for applications has been illustrated through simulation using electromagnetic CAD software. The proposed design has been confirmed to function as a Wi-Fi, Bluetooth, and C band spatial filter for automotive applications.

The initial structure presented a notch at 2.07 GHz, while the bended structures provided stopbands at: 4.90 GHz and 5.01 GHz (for positive bending) and also at 4.65 GHz and 4.90 GHz (for negative bending). Tunability can be further enhanced by modifying the width of the structure or the substrate thickness.

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