Single/dual-band frequency and polarization switching using frequency selective surfaces for terahertz applications

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Abstract
This paper presents reconfigurable frequency and polarization FSS-based with photoconductive switches in a single and dual-band operation for antenna applications at the terahertz band. The single band FSS unit-cell element exhibits frequency reconfigurability between 0.62 and 0.7 THz. It also converts the LP waves into CP over a frequency band ranging from 0.59 to 0.8 THz (30% 3-dB BW). The dual-band FSS unit-cell element exhibits frequency reconfigurability between (0.42 and 1.03 THz) when the switches are turned ON and (0.51 THz and 0.865 THz) when the switches are turned OFF. Moreover, it exhibits polarization conversion over two bands from 0.46 to 0.56 THz (20% 3-dB BW) and from 0.82 to 0.91 THz (12% 3-dB BW). The dual-band FSS unit-cell element is arranged in a 7 × 7 array and used as a reflector for two dipole antennas (A and B) operating at 0.82 THz and 0.5 THz, respectively. The same dual-band FSS-based surface enhances their gain to about 8.4 dBi and converts their polarization from LP to CP at 0.82 THz and 0.5 THz, respectively.

Keywords FSS · Terahertz band · Polarization converter · Metasurface

1 Introduction

The main issue that affects the propagation link budget is the mismatching of the polarization at the receiving side of most wireless communication applications. In satellite communication, the linearly polarized (LP) wave may be rotated while transferring from the transmitting side and the receiving side. The rotation of the linearly polarized wave is named “Faraday rotation,” which raises the funds of the propagation link (Maral and Bousquet 2009). This issue decreases the usage of linearly polarized waves in wireless applications (Boutejdar et al. 2015). Also, the linearly polarized waves have another issue called multipath fading. This issue usually occurs because of the transmission and the antenna’s
orientation at the receiving side. The advantages of the circularly polarized waves increase the necessity of using them instead of the linearly polarized waves for wireless communications applications (Mahmoud et al. 2021; Lin et al. 2020; Qi et al. 2020). The high immunity against the transmission medium effects is the essential advantage of the circularly polarized waves (Fahad et al. 2020; Baghel et al. 2019). To convert a linearly polarized wave to a circularly polarized wave, the researchers began to design aided configurations that can obey that conversion called polarization converters (PC) (Yassin et al. 2019). Different surfaces can be used to convert the linearly polarized wave from the antenna to a circularly polarized wave. Such surfaces may be designed based on periodic structures like the artificial magnetic conductors (AMC) (Tao et al. 2019), and frequency-selective surfaces (FSS) (Chen and Zhang 2018). Other surfaces are based on metamaterials (MM) which are defined as artificial structures that have a negative real part of electrical permittivity ($\varepsilon$), a negative part of magnetic permeability ($\mu$), and a negative real part of refractive index ($n$) at the operating frequency of the antenna (Edries et al. 2020).

Polarization conversion includes converters that adopt the practice of combining metamaterials with split-ring resonators (SRR) (Martinez-Lopez et al. 2014) as well as the practice of using frequency selective surfaces (FSS) (Joyal and Laurin 2014), some of which utilize multiple layers (Tarn and Chung 2007). SRR is an artificial structure being explored in telecommunication for its effect on magnetic susceptibility.

FSS is a concept that consists of repetitive planar arrangements of metallic elements on a dielectric substrate and utilizes a surface of repeated structures that has seen applications in antennas for its ability to transmit and receive selected electromagnetic fields (So et al. 2013). FSS can break down a single wave into two elements of almost equal power with a phase difference of $90^\circ$. This is because of the inductive and capacitive behaviors found in FSS produced in perpendicular directions and allow for wave decomposition. FSS holds multiple advantages such as showing effects of improved antenna gain, as proven in Chiu and Chen (2011) where the incorporation of an FSS superstrate produced a circularly polarized resonant antenna with a high gain, in addition to more control over antenna beam-width, as studied in Wang (2014) where a frequency selective surface was used to control the beam-width of an antenna. The FSS technology is comparatively easy to install but poses a trade-off to make it reconfigurable, were to increase the electromagnetic performance, its complexity increases, and therefore its fabrication procedure’s simplicity slightly decreases. Besides, to give the converter reconfigurable features, the number of elements must heavily increase (Li et al. 2015).

Reconfigurability gives an antenna substantial merit. Multiple studied applications give reconfigurable converter features, such as the addition of PIN diodes (Raman et al. 2013), liquid crystals (Doumanis et al. 2014), varactor diodes (Row and Tsai et al. 2014), or the usage of microelectromechanical systems (MEMS) (Debogović et al. 2014). Each of which plays a vital role in the benefits and drawbacks mentioned above. The application of FSS has been lately considered for use in the terahertz band, which had been comparatively less explored due to its complexity, lack of needed components, and the easy obstruction of its waves caused by their small size. Even today, terahertz waves have posed a challenge to researchers in intercepting and guiding (Singh et al. 2016).

Terahertz frequency band currently holds an appealing position in researchers’ eyes due to being the potential successor to the fifth generation (5G). It may provide extra features such as the possible decrease in transceiver size and better energy efficiency, as seen in Petrov et al. (2016), which discusses all the so-far known challenges and standardizations needed for the terahertz band, as well as all its potential applications. By manipulating the layout and shape of the structure of the FSS, it produces an effect on the electromagnetic
waves that, in exchange, cause suppression of specific frequencies and passage of other frequencies. Through an intricate design, intercepting terahertz waves may be possible through FSS integrated systems.

This paper presents a reconfigurable linear to circular polarization converter that operates on the terahertz band, contrasting to most converters that operate on gigahertz bands. The converter is based on the FSS layout, which in addition to its previous benefits, also boasts its low-profile structure and relative ease of fabrication. The designed converter is simulated based on CST-MW studio, powerful software for computing devices’ effect in a virtual electromagnetic environment. The produced plots will be later displayed, along with an analysis of the obtained results. In the following sections, the basic design of the converter and the methods used will be discussed. The chronological steps used to attain the final results are also included to highlight different techniques’ effects. A discussion of the obtained results and the overall conclusion of the performed research are introduced at the end of this paper.

2 Frequency reconfigurable FSS unit-cell element

2.1 Initial design

This paper starts with the design of a primary unit cell of the converter. As the end product is a frequency selective surface composed of repeated small elements, the term “unit cell” is suitable to describe these components that make up the lattice-like surface. The unit cell has a metasurface and uses silicon as a substrate with a dielectric constant ($\varepsilon_r$) of 11.9 and a thickness of $h = 60 \, \mu m$. It has a side-length of $L = 60 \, \mu m$, the width of $W = 79.35 \, \mu m$, and three slots each of gap-width $d = 2 \, \mu m$ as shown in Fig. 1. The FSS unit cell’s internal design took the shape of a bee-hive-like dual hexagonal structure of a side length of 20 µm and placed it at both sides of the substrate.

Six photoconductive switches are then added at the upper and lower slots and vary between ON and OFF states, as shown in Fig. 2. Photo-conductive switching elements are manufactured based on semiconductors like gallium-arsenide (GaAs) and silicon (Si) (Pendharker et al. 2014). Using photoconductive switches for reconfigurability eliminates the
usage of biasing lines and connecting wires, resulting in higher isolation, lower interference, and significantly higher switching speed than the other switching elements (Sodré Junior et al. 2014). The photo-conductive switch is used in antennas to achieve the pattern, polarization, and frequency reconfigurability (Parchin et al. 2020). Here, the photoconductive diodes are used to achieve frequency reconfigurability.

This unit-cell element is analyzed using Floquet boundary in CST-MW studio. It was found that when the photoconductive switches are turned ON, the magnitudes of the reflection and transmission coefficients of the proposed FSS unit-cell element have the same value at $-3$ dB (at 0.55 THz) and a fixed phase difference of $\Delta \phi = 90^\circ$ over the operating frequency band from 0.35 to 0.69 THz as shown in Fig. 2.

When the switches turned OFF, the minimum value of $S_{11}$ shifted to 0.62 THz. The magnitudes of the reflection ($S_{11}$) and transmission ($S_{21}$) coefficients of the proposed FSS unit-cell element have the same value at $-3$ dB (at 0.5 THz) and a fixed phase difference of $\Delta \phi = 90^\circ$ over the operating frequency band from 0.35 to 0.59 THz as shown in Fig. 3.

![Fig. 2](image2.jpg)  
*Fig. 2* The variation of a the magnitude and b the phase of the reflection and transmission coefficients of the proposed FSS unit-cell element when the switches are turned ON

![Fig. 3](image3.jpg)  
*Fig. 3* The variation of a the magnitude and b the phase of the reflection and transmission coefficients of the proposed FSS unit-cell element when the switches are turned OFF
This frequency reconfigurable FSS unit-cell element can be arranged in a periodic structure and used for antennas enhancing their gain values, as discussed through this paper.

### 2.2 Dual-band reconfigurable FSS unit-cell element

Based on the previous research study for a stopband filter (Xu et al. 2018) which implements the use of a Jerusalem cross shape, a cross-like shape is implemented to the initial unit cell design, where a vertical line intersects the hexagon. Each vertical line has its own perpendicularly intersecting horizontal line of 7 µm length and said the horizontal line has two 6 µm vertical lines at each end, as shown in Fig. 4.

It was found that when the photoconductive switches are turned ON, the magnitudes of the reflection and transmission coefficients of the proposed FSS unit-cell element have the same values at 0.42 THz and 1.03 THz. It also can operate over two frequency bands with center frequencies 0.56 THz and 1.07 THz, as shown in Fig. 5a. The phase
difference of $\phi = 90^o$ is obtained over the dual-bands (from 0.35 to 0.58 THz) and (from 0.59 to 1.0 THz) as shown in Fig. 5b.

When the switches are turned OFF, new frequency bands are obtained with minimum $S_{11}$ values at frequencies of 0.52 THz and 0.84 THz, as shown in Fig. 6a. Also, the phase difference of $\Delta \phi = 90^o$ is obtained over the dual-bands (from 0.35 to 0.5 THz) and (from 0.73 to 0.85 THz) as shown in Fig. 6b. Switching the photoconductive diodes enables the proposed FSS unit-cell element to operate at four different operating frequencies for terahertz range’ applications.

3 Polarization reconfigurable FSS unit-cell elements

3.1 Conversion fundamentals

In both forms of polarization (linear and circular), the electromagnetic wave travels at a uniform rate. A linearly polarized wave oscillates over a specific axis (propagation direction), while the circularly polarized wave rotates along the axis. For theoretical conversion from linear to circular polarization, a couple of rules need to be taken to account. The transmitting wave is a superposition of two orthogonal elements of the same magnitude. The amplitude can be represented by $E^l$ can be found in Liu et al. (2015):

$$\vec{E}' = \vec{E}'_x + \vec{E}'_y = E_0'(T_x \hat{x} + T_y \hat{y})e^{-jkz} \tag{1}$$

where $T_x$ and $T_y$ are reflections and transmission parts of the transmission matrix $[T]$:

$$\begin{bmatrix} T_x \\ T_y \end{bmatrix} = \begin{bmatrix} |T_x|e^{-j\phi_x} \\ |T_y|e^{-j\phi_y} \end{bmatrix} \tag{2}$$

For the conversion to occur, two conditions must be obtained at the operating frequency, which is stated as follows:where

![Fig. 6](image) The variation of a the magnitude and b the phase of the reflection and transmission coefficients of the proposed dual-band FSS unit-cell element when the switches are turned ON
\[ |T_x| = |T_y|, \text{ and } \Delta \varphi = \pm 90^\circ. \]

\[ \Delta \varphi = \varphi_x - \varphi_y \]  \hfill (3)

The two FSS unit-cell elements in the previous section satisfy the fundamentals of linear to circular polarization conversion. To confirm the unit-cell element’s conversion credibility, the axial ratio concerning frequency is constructed. The transmission coefficients of both fields are represented in the equation as \( T_{xx} \) and \( T_{yy} \), which in Figs. 4 and 6 gave an outcome of equal coefficients with \( \pm 90^\circ \) phase difference, proving the generation of a correct circularly polarized wave (Zhang et al. 2020).

\[ AR = \frac{10 \log_{10} \left( T_{xx} \cos \tau + T_{yy} \cos \Delta \Phi \sin \tau \right)^2 + T_{yy}^2 \sin^2 \Delta \Phi \sin^2 \tau}{\left( T_{xx} \sin \tau + T_{yy} \cos \Delta \Phi \cos \tau \right)^2 - T_{yy}^2 \sin^2 \Delta \Phi \cos^2 \tau} \]  \hfill (4)

\[ \tau = 1/2 \tan^{-1} \left( \frac{2T_{xx} \cos \Delta \Phi}{T_{xx}^2 - T_{yy}^2} \right) \]  \hfill (5)

3.2 Results and analysis

For the single band FSS unit-cell element, the axial ratio is calculated when the photoconductive switches are turned OFF and ON. It was found that the proposed single band FSS unit-cell element shown in Fig. 1 has a wide 3-dB axial ratio band from 0.59 to 0.8 THz (30% 3-dB BW) if all switches are at OFF state as shown in Fig. 7a. This is mean that the unit-cell element suitable for polarization conversion applications at that band of frequencies. However, when all switched turned ON, the proposed FSS unit-cell element lost the polarization conversion conditions.

![Fig. 7](image)

Fig. 7 The variation of axial ratio versus frequency for (a) the single-band and (b) the dual-band FSS unit-cell elements when the switches are turned OFF and ON.
The dual-band FSS unit-cell element shown in Fig. 4 had a polarization conversion property when the switches turned OFF. It exhibits dual 3-dB AR bands; the first one ranging from 0.46 to 0.56 THz (20% 3-dB B.W) and the other ranging from 0.82 to 0.91 THz (12% 3-dB B.W) as in Fig. 7b. So, the dual-band FSS-based unit-cell element is suitable for polarization conversion of different antennas with operating frequencies within these two bands.

As seen in Table 1, which details the proposed converter’s features concerning other converters, this converter excels in operating at dual-band resonance, contrasting with the rest of the converters. Its terahertz frequency focus results in having proportionally smaller dimensions. Its meager size would be ideal for implementation in any area or device, as its near-negligible dimensions fit modern size constraints imposed by the advancement of technology and the necessity to take up the least space as possible.

4 High gain reconfigurable polarization conversion dipole antenna

4.1 Proposed dipole antenna design

Two linear polarized (LP) dipole antennas are designed to resonate at the frequency of 0.82 THz and 0.5 THz as applications for the dual-bands FSS-based unit-cell elements. These proposed antennas are placed over an N×N FSS array through the next section adding polarization reconfigurability feature to them, enhancing their gain, and enabling polarization reconfigurability.

The first proposed dipole antenna (antenna A) that resonates at 0.82 THz consists of a rectangular perfect electric conductor (PEC) of side length $L_d = 125 \, \mu\text{m}$ and width $W_d = 12 \, \mu\text{m}$. The dipole antenna’s radiator is placed over a square-shaped substrate of relative permittivity of $\varepsilon_r = 3.38$, a side length of $L_s = 200 \, \mu\text{m}$ and height of $H_s = 10 \, \mu\text{m}$ as shown in Fig. 8a. This antenna operates over a $-10 \, \text{dB}$ bandwidth ranging from 0.76 to 0.91 THz (18% BW), as shown in Fig. 8b. The proposed 0.82 THz dipole antenna radiates an LP wave omnidirectionally with a maximum gain value of 2.47 dBi, as shown in Fig. 9a. The 2D components of the radiated left (EL) and right (ER) hand electric field are equal at the operating frequency, as shown in Fig. 9b.

The second proposed dipole antenna (antenna B) that resonates at 0.5 THz has the same structure of the first one but with scaled dimensions as shown in Fig. 10a. This antenna operates over a $-10 \, \text{dB}$ bandwidth ranging from 0.46 to 0.55 THz (18% BW), as shown in Fig. 10b. The proposed 0.5 THz dipole antenna radiates an LP wave omnidirectionally with a maximum gain value of 2.69 dBi, as shown in Fig. 11a. The 2D components of the radiated left (EL) and right (ER) hand electric field are equal at the operating frequency, as shown in Fig. 11b.

4.2 The proposed dipole antennas over N×N dual-band FSS unit-cell element

The proposed dual-band FSS unit-cell element when all switches turned OFF is arranged in N×N periodic surface and used as a reflector for the antenna (A), as shown in Fig. 12 where N is the number of the FSS unit-cell elements. N value is varied from three; the value enables the FSS surface to cover the dipole antenna’s surface area. Then the value of N is increased to detect the optimum value that produces the height gain.
### Table 1 A comparison between the proposed converter and other polarization converters

| References          | Used technique | Unit cell area | $F_0$ (GHz) | 3 dB AR B.W (GHz) | Used material | Operating bands | Configuration with antenna | Overall size and cost |
|---------------------|----------------|----------------|-------------|-------------------|---------------|------------------|----------------------------|----------------------|
| Lin et al. (2020)   | MM             | 8 × 8 mm²      | 14          | 14.5              | PEC           | Single-band     | N/A                        | High                 |
| Fahad et al. (2020) | MM             | 5.2 × 5.2 mm²  | 25          | 5/7.5             | Cu            | Dual-band       | Introduced for only single band | High                 |
| Liu et al. (2015)   | MM             | 0.19 × 0.19 mm²| 1250        | 460               | Au            | Single-band     | N/A                        | High                 |
| Cheng et al. (2014) | MM             | 0.11 × 0.11 mm²| 1000        | 200               | Au            | Single-band     | N/A                        | High                 |
| This article        | FSS            | 0.79 × 0.6 mm² | 500/820     | 150               | Al            | Dual-bands      | Introduced for both bands   | Low                  |
The dipole antenna (A) is placed over the FSS surface at a distance \( (h) \). A parametric study for this height value is done. It was found that, as the number of the unit-cell elements increases, the matching values also increase, as shown in Fig. 13. So, the FSS array of \( 7 \times 7 \) achieved the best matching values were obtained for \( h_3 = 0.5 \lambda_o \) (\( \lambda_o \) is the operating wavelength).

For \( N = 7 \), when the proposed dipole antenna (A) is placed at a distance of \( h_1 = 0.1 \lambda_o \), no matching is achieved, as shown in Fig. 12c. This means the array did not behave as an FSS surface, and the radiation pattern of the dipole antenna did not reflect as in Fig. 13a. If this distance increased to \( h_2 = 0.25 \lambda_o \), a wide frequency bandwidth from 0.71 to 0.95 THz (30% B.W) is obtained as in Fig. 13c. Moreover, a single reflected beam with a maximum value of 8.48 dBi is obtained at 0.83 THz, as shown in Fig. 14b. However, if the antenna is placed at the height of \( h_3 = 0.5 \lambda_o \), the reflected beam is diffracted into two directions, and the maximum gain values decreased to 6.32 dBi, as shown in Fig. 14c.
Fig. 10  a The first proposed dipole antenna construction and b the variation of its reflection coefficient versus frequency

Fig. 11  a The dipole antenna’s radiation pattern in three dimensions and b the two-dimensional components of the radiated electric field of the dipole antenna

Fig. 12  The periodic structure of the dual-band FSS unit-cell elements as a reflector for the proposed dipole antenna (A) for a N = 3, b N = 5, and c N = 7
The optimum configuration results are obtained when the proposed dipole antenna (A) is placed at a distance of 0.25 \( \lambda_0 \) over 7 × 7 FSS surface with a surface area of 420 \( \mu \text{m} \times 555.45 \mu \text{m} \). Moreover, plotting the 2D left and right components of the radiated electric field indicates that the FSS surface succeeds in converting the dipole antenna’s linear polarized wave into circularly polarized at a frequency of 0.82 THz, as shown in Fig. 15a. When the photoconductive switches are turned ON, the FSS unit-cell is no longer able to achieve polarization conversion where \( E_R \) and \( E_L \) have the same values, as shown in Fig. 15b.

For the optimum configuration settings of the antenna over an FSS-based array, the proposed dipole antenna (A) is replaced by antenna (B) as an application for the FSS band ranging from 0.46 to 0.56 THz. It was found that the 2D left and right components of the radiated electric field are equal, indicating that the FSS surface succeeds in converting the dipole antenna’s linear polarized wave into circularly polarized at a frequency of 0.5 THz as shown in Fig. 16a. When the photoconductive switches of the FSS unit-cell elements are turned ON, the FSS unit-cell is no longer able to achieve polarization conversion where \( E_R \) and \( E_L \) have the same values, as shown in Fig. 16b.

It was found that when the photoconductive switches of the unit-cell elements are turned OFF, the linear polarized waves of both antennas are converted into circularly polarized waves. The axial ratio of the two antennas is calculated and figured, confirming the ability of the proposed FSS-based surface to perform polarization conversion for two different antenna with two different operating frequencies, as shown in Fig. 17. Antenna (A) has a 3 dB axial...
ratio band ranging from 0.8 to 0.98 THz (19.5% 3 dB-AR BW), and antenna (B) has a 3 dB axial ratio band ranging from 0.47 to 0.61 THz (28% 3 dB-AR BW). So, the proposed dual-band FSS-based unit-cell element can be arranged for polarization conversion for two different antennas or dual band antenna, as in section three. Each antenna has an operating frequency within either two bands of the dual-band FSS unit-cell elements.

Fig. 15 The 2D components of the radiated electric field of the dipole antenna (A) over 7 × 7 FSS surface a when all switches are turned OFF and b when all switches are turned ON.

Fig. 16 The 2D components of the radiated electric field of the dipole antenna (B) over 7 × 7 FSS surface a when all switches are turned OFF and b when all switches are turned ON.
5 Conclusion

A frequency reconfigurable single and dual-band terahertz polarization converter with a hexagon-shaped polarizer utilizing FSS technology was studied and presented. The single band FSS unit-cell element exhibited frequency reconfigurability and polarization conversion in a wide band of frequencies from 0.59 to 0.8 THz (30% 3-dB BW). The dual-band FSS unit-cell element exhibited frequency reconfigurability and polarization conversion over two frequency bands from 0.46 to 0.56 THz (20% 3-dB BW) and from 0.82 to 0.91 THz (12% 3-dB BW). The dual-band FSS unit-cell element is arranged in a $7 \times 7$ array and used as a reflector for two different dipole antennas, enhancing their gain to approximately 8.4 dBi and converting their polarization from LP to CP over two different frequency bands. The proposed dual-bands FSS-based unit-cell element is suitable for polarization conversion for different antennas that have operating frequencies within the two bands. This advantage suppresses the need to design and use a large number of different surfaces for each antenna operating frequency. The converter is adequate to operate at the terahertz bands and is sufficient for deployment.

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