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Abstract

A circular polarized (CP) infrared (IR) leaky wave surface design is presented. The metasurface consists of an array of rectangular patches connected by microstrip and operating over the long-wave infrared (LWIR) spectrum with directional wave emission and absorption. The surface is composed of periodically aligned arrays of sub-wavelength metal patches separated from a ground plane by a dielectric slab. The design combines the features of the conventional patch and leaky wave antenna leading to a metasurface that preferentially emits CP IR radiation by use of axial asymmetrical unit cells. This is a deviation from reported structures that mainly employ a phase shifter to combine linearly polarized waves in order to attain circular polarization. The performance of this leaky wave surface is verified through full-wave simulation using the ANSYS HFSS finite element analysis tool. The leaky wave phenomenon is demonstrated by the frequency and angular dependence of the absorption while circular polarization is characterized via stokes parameters. The main beam of this surface can be steered continuously by varying the frequency while maintaining circular polarization within the main beam direction. A CP leaky wave at 10.6 μm with a scanning angle of 30° is demonstrated. Metasurfaces exhibiting spectral and polarization selectivity in absorption/emission hold the potential for impact in IR applications including detection, imaging, thermal management, energy harvesting and tagging.

Key words: infrared, stokes vector, metasurface, circular polarization, leaky wave antenna.

I. INTRODUCTION

Metasurfaces are 2D surface versions of metamaterials. They are artificially engineered materials to achieve some unique electromagnetic properties not achievable by a single material in nature[1, 2]. The construction of metamaterials is usually performed by periodically arranging a set of scatterers with subwavelength periodicity in a host medium to obtain some desired electromagnetic properties[2]. Due to the 2D configuration of metasurface, they tend to occupy less space and are less lossy than metamaterials[1, 2]. An overview of metasurfaces and possible applications has been presented[1]. In this study, the basic building block of the metasurface is a microstrip patch and is arrayed periodically in x and y dimensions. Microstrip patches have several attractive features including low profile, lightweight, conformability to various mounting structures and simplicity of fabrication. In addition, they have the demonstrated potential for making circularly polarized (CP) antennas at microwave frequencies. Circular polarized systems can enhance a wireless system capacity since research has shown that CP waves are more fade resistant than linearly polarized (LP) waves[3, 4,5]. This has led to their use in the crowded and noisy environment of radio frequency communications in addition to sensors, and radar. Additional merits of CP are that it eliminates polarization mismatch losses[6] and can also receive a linearly polarized waves[7]. While microstrip patches suffer from poor radiation efficiency and large losses, leaky wave antennas (LWAs) are efficient low loss structures[8], hence a combination that integrates circular polarization, microstrip patches and leaky wave designs merits an investigation to come up with a metasurface that possess a synergy of the three. Most of the conventional LWAs are linearly polarized and a CP LWA has been presented[10]. This structure requires two LWAs and a phase shifter for CP wave generation. In this paper, we have considered a single fed patch with axial asymmetry leading to CP. Single fed circularly polarized patches are very attractive, because they can be arrayed and fed like any linearly polarized patch. However a single-fed design generally provides narrow axial-ratio bandwidth[10].

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Although the existence of planar leaky wave antennas is a well known topic[12], limited research has been undertaken at LWIR spectral range. A frequency selective surface at LWIR has been presented[14]. In this work, we design and characterize a metasurface based on a patch antenna array to create a circular polarized leaky wave surface. This metasurface is of special interest because it can be fabricated using standard lithography methods and differs from previous reports because we have considered for the first time a circularly polarized metasurface operating at LWIR range. Because thermal IR radiation from the natural environment is not CP, there are applications where it is desirable to produce directional CP radiation. This has potential for impact in IR applications including detection, imaging, and tagging.

II. THEORY

Planar leaky antennas leak power from the travelling waves propagating along the antenna surface. Beam shaping of a leaky wave antenna is through independent control of phase and leakage constant along the antenna[11]. Due to leakage, the propagation constant is complex where the imaginary part is the attenuation constant α and the phase constant β is the real part[12]. The longitudinal wave number of a propagating wave is given by

$$k = \beta - j\alpha \tag{1}$$

Since the phase constant β is a function of frequency, the beam direction can be scanned by varying the frequency. This is advantageous in the sense that electronic beam control is described as an alternative way for beam steering at a given frequency. A large α means that the power that leaked away (radiated) or dissipated per unit length is large and leads to a short effective aperture length and a large beam width[12].

The angle of radiation for the leaky beam with respect to the normal of the structure is given by[12]

$$\theta_0 = \sin^{-1}\left[\frac{\beta(\omega)}{k_0}\right] \tag{2}$$

where $\beta(\omega)$ is the frequency-dependent phase constant and $k_0$is the free space wave number.

A one dimensional (1D) LWA can be arrayed in two dimensions to achieve a metasurface that is leaking at a certain angle. This surface can also act as a reflective surface with directional absorption. The spectral emissivity for a reflective surface is given by[13,14]

$$\varepsilon(\lambda, T) = A(\lambda, T) = 1 - R(\lambda, T) \tag{3}$$

where λ is the wavelength of radiation, A and R are the absorptivity and reflectivity of the surface, respectively, and T is the temperature in Kelvin of the emissive structure. Stokes parameters were introduced as a convenient way to describe partial polarized waves characterized by observable power terms and not by amplitudes (and phases). The Stokes parameters are sufficient to characterize the magnitude and the relative phase, and hence the polarization of a wave. Stokes parameters are given by the Stoke vector coefficients of the form[13]

$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \langle \varepsilon_s \rangle + \langle \varepsilon_p \rangle \\ \langle \varepsilon_s \rangle - \langle \varepsilon_p \rangle \\ 2.\langle \sqrt{\varepsilon_s . \varepsilon_p} . \cos(\delta) \rangle \\ 2.\langle \sqrt{\varepsilon_s . \varepsilon_p} . \sin(\delta) \rangle \end{bmatrix} \tag{4}$$

Here δ is the phase shift between the two orthogonal components of the polarized emissivity and S_0 S_1 S_2 and S_3 are the Stokes vector elements. The Stokes parameter S_0 is always equal to the total power (density) of the wave, S_1 is equal to the power in the linear horizontal or vertical polarized components, S_2 is equal to the power in the linearly polarized components at tilt angles $\delta = 45^0 or\ 135^0$ and S_3 is equal to the power in the left-handed and right-handed circular polarized components[13]. If any of the parameters S_0, S_1 , S_2 or S_3 has a non-zero value, it indicates the presence of a polarized component in the propagating wave and often the Stokes parameters are normalized by dividing with S_0 .

III. MODELING

Figure 1 denotes the unit cell critical dimensions considered. The patch portion has $x \times y$ dimensions of $2.6 \times 2.157\mu m$ respectively. The dimensions of the unit cell $p \times q$ were 3.85×4.3625 μm, while the offset d from the y axis was 0.45 μm. The periodic patches are connected with Au microstrip of width 0.65 μm. The substrate has a thickness of 0.65 μm while the patch and the ground plane are 75nm and 100nm thick, respectively. The material thickness was electrically small otherwise a thick and low dielectric constant substrate yields large bandwidth, while spurious radiation also increases with substrate thickness[6]. The aim of the design was to have a CP beam scanning within the LWIR range (20-40THz).The modeling was driven modal in ANSYS HFSS, with material properties obtained from spectroscopic ellipsometry (IR-VASE, J.A. Woollam)[15]. Master/slave boundaries were employed to simulate an infinite array of patches. The geometry considered here has gold (Au) conductor and low permittivity zinc sulfide (ZnS) substrate.

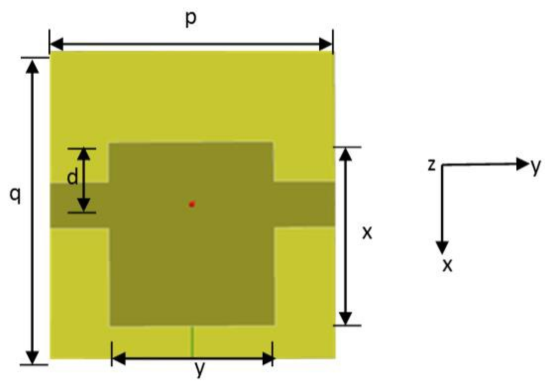


Figure 1 Model setup

IV. RESULTS

The dispersion characteristic of the metasurface is shown in Figure 2. Broadside radiation is around 30THz and 37THz. It will be shown later that 37THz corresponds to a patch mode. At broadside leaking, $\beta \approx 0$ and this frequency can be denoted as f_0. When the leaking frequency drops below f_0 i.e < 0 , the propagating mode will be directed in the backward propagation direction[17]. From Figure 2, we note backward leaking between 25-30THz. Below 25THz we have a bound wave (surface wave).This is in the region below the light line as noted from Figure 2.

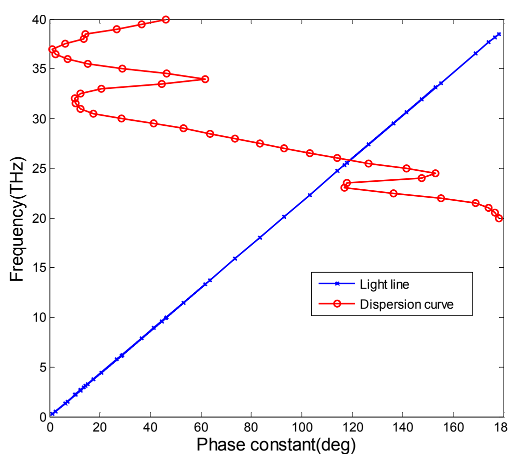


Figure 2 Dispersion curve plot

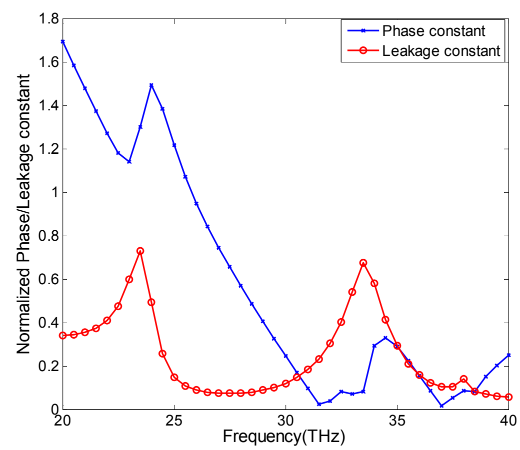


Figure 3 Normalized Phase and leakage constant plot

The normalized phase and leakage constant are shown in Figure 3. The phase constant should be lower than that of free space (β<k_o) for a leaky wave to occur. It can be noted that the normalized phase constant (β) is frequency scanned between 25-32THz. This region depicts a leaky wave region. Within this range, the leakage constant (α) is relatively constant. A region where $\beta \leq \alpha$ denotes regions of broadside leaking for uniform and quasi uniform structures[12].

Circular polarization in the model is due to the asymmetry about the longitudinal axis. Figure 4 shows a vector surface plot on the $X - Z$ plane for a symmetrical case. Vector plots use arrows to illustrate the magnitude of the x, y and z components of the field. The vector field distribution in figure 4 is both symmetrical for both left and right side of the figure. The edge voltages on the top patch is given by

$$v \approx -E_z h \tag{5}$$

Where h is the thickness of the substrate and the negative sign defines the voltage from the edge conductor to the ground conductor. Due to symmetry, the voltage potentials at the extreme patch edges are equal and there is no potential difference on the patch edge along the x axis, ultimately the net scalar field quantity on the patch along the x axis, $E_x \approx 0$.

For the longitudinal asymmetrical case caused by a shift along the x axis, there is unequal distribution of E vector between the two sides along the x axis as shown by the circled region in Figure 5. Hence a potential difference exists between these two opposite edges and effectively E_x is non-zero. For transverse axis symmetry and asymmetry ($Y - Z$ plane), E_y is always non zero due to phase variation of the travelling wave in this direction[16] . E_x and E_y are orthogonal complex valued field components, and if neither is zero, then CP exists. Phase quadrature between E_x and E_y in planar rectangular geometries has been theoretically proved[16]. The existence of quadrature phase difference between E_x and E_y results in circular polarization[16,17].

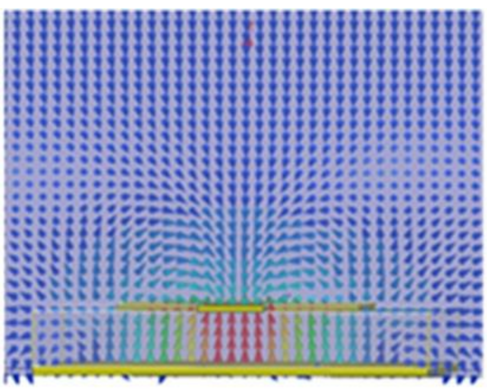


Figure 4 E-vector field (Symmetrical case)

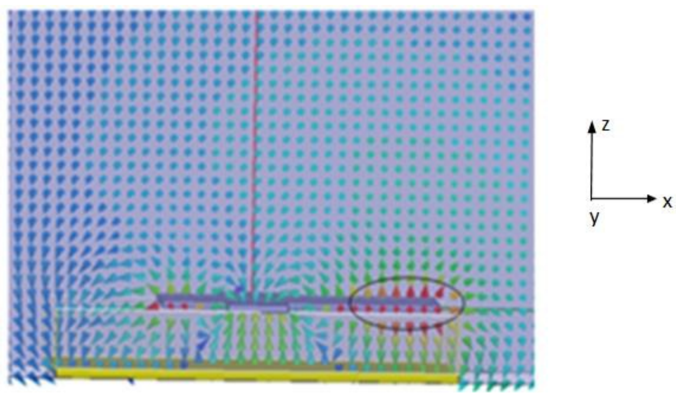
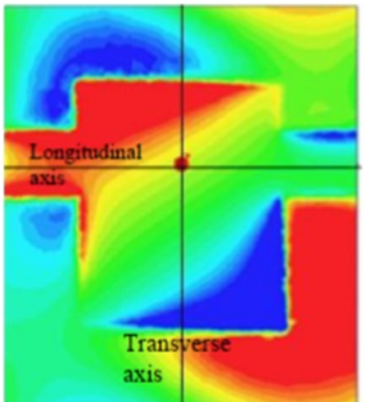


Figure 5 E- vector field (Asymmetrical case)

Figure 6 and 7 illustrates E-field at phase distribution at 28.5 THz. It can be noted that E_x and E_y corresponding to transverse and longitudinal electric fields respectively are in phase quadrature in axially asymmetrical leaky wave patch and inherently elliptically polarized[16]. The E_x field component is controlled by the degree of longitudinal asymmetry and can be tuned to achieve CP.



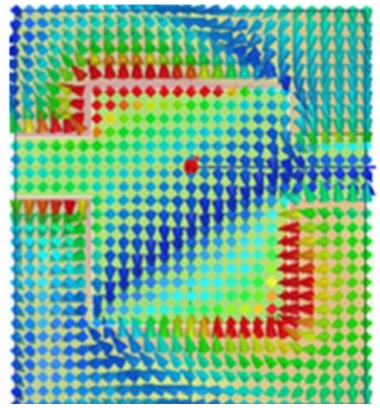


Figure 6 E-field at phase

Figure 7 E-field vector plot

We have illustrated CP by plotting of Stokes vector parameters. The Stokes vector parameters gives a direct physical interpretation of the state of polarization of a given EM field and the polarized emissivity is computed via calculating power reflection coefficient using Kirchhoff's law[13]. A plot of stokes vector is shown in the following set of figures.

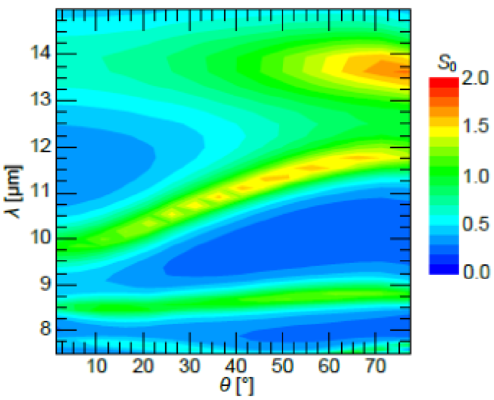


Figure 8 Total Intensity plot S_0

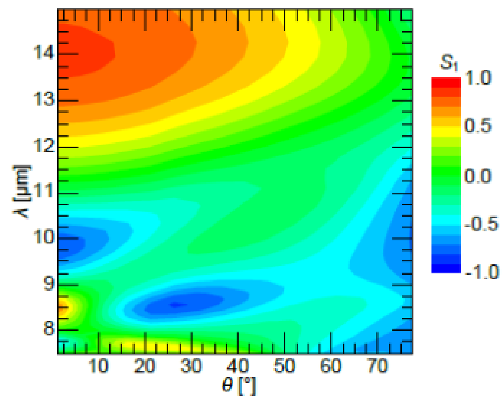


Figure 9 Linear polarization plot S_1

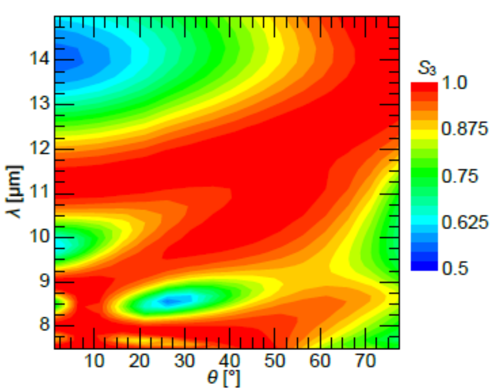


Figure 10 Circular polarization plot S_3

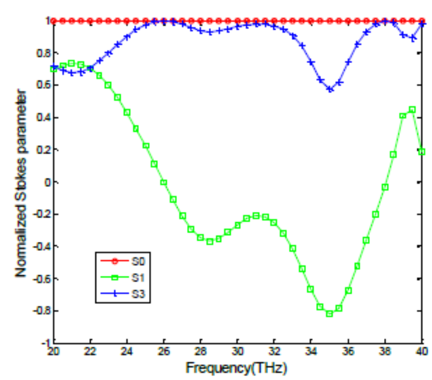


Figure 11 Stokes parameter plot

Figures 8, 9 and 10 illustrates simulated variation of S_0, S_1 and S_3 Stokes parameters with frequency and angle, respectively. S_0 denotes the intensity of the leaked wave. It can be noted that the total intensity closely correlates with the frequency scanning curve of Figure 2 and denotes broadside operation at 32 and 37THz. S_0 has a frequency scanned beam at 10-12.5μm. A patch mode is also noted at 9μm while in 13.5-14.5μm range, some energy attributed to TE mode is noted. S_1 denotes linear polarized wave. Linear polarization can be horizontal, $S_1 \approx 1$ or vertical $S_1 \approx -1$. In the field plot Figure 9, it can be seen that LP exists at wavelengths 12.5um and above and it's low in the other frequency ranges, though some pockets of vertical LP exist for some angles at 9 and 10 μm ranges. In Figure 10 we have illustrated S_3 by setting a threshold of 0.5-1.0 for CP. It can be seen that the spectral range 7-13.5μm is predominantly CP and within this range the metasurface reveal a high degree of RHCP indicated by the near-unity value of S_3. Linear plots of Stokes parameters normalized to S_0 are shown in Figure 11 for a 30^0 incident wave. The S_1 plot predicts weak LP in the leaky region 26-30THz, while the S_3 plot depicts strong CP. Figure 12 shows frequency scanning of the leaking wave. The span angle is noted from broadside to 75^0 off broadside for the backward leaking wave. Frequency scanning is a signature characteristic of a leaky mode.

Figure 13 shows an angular normalized S_0 intensity plot (emissivity). The results depict frequency scanning with approximate predicted angles. At 10.5um, the leaking angle is around 28^0.

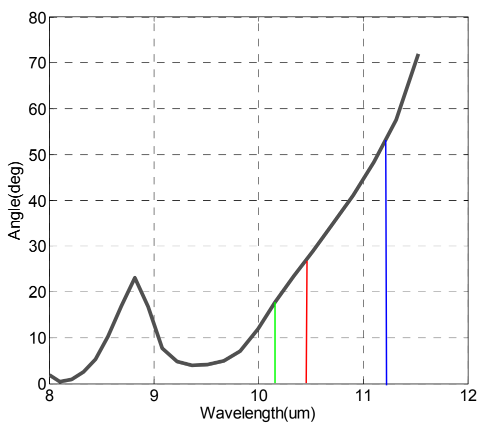


Figure 12 Leakage angle plot

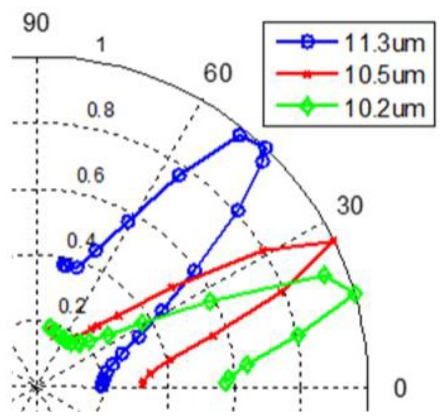


Figure 13 Angular emmisivity plot

V. CONCLUSION

The CP leaky wave surface has been simulated and characterized. It has been noted that the axial asymmetry has a direct impact on polarization. The higher the asymmetry, the polarization becomes strongly circular. However as the asymmetry is increased, it has been noted that the frequency scanning phenomena diminishes. It means that although the propagated wave is increasingly circular polarized, the leaky property diminishes and the patch radiation effect is taking preeminence over leaky wave phenomena. In this paper an attempt has been done to exploit the patch asymmetry to achieve circular polarization while simultaneously achieving the beam scanning advantages of leaky wave metasurface at LWIR range.

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