Polarized infrared emission using frequency selective surfaces

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Abstract: An emission frequency selective surface, or eFSS, is made up of a periodic arrangement of resonant antenna structures above a ground plane. By exploiting the coupling and symmetry properties of an eFSS, it is possible to introduce polarization sensitive thermal emission and, subsequently, coherent emission. Two surfaces are considered: a linearly polarized emission surface and a circularly polarized emission surface. The linearly polarized surface consisted of an array of dipole elements and measurements demonstrate these surfaces can be fabricated into high polarization contrast patterns. The circularly polarized surface required the use of an asymmetrical tripole element to maintain coherence between orthogonal current modes and introduce the necessary phase delay to realize circularly polarized radiation.

OCIS codes: (290.6815) Thermal Emission; (160.3918) Metamaterials; (230.5440) Polarization-selective devices.

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1. Introduction

The formation of thermally excited, coherent emission using planar surfaces has been investigated over the past few years for potential applications in efficient energy harvesting [1] and related fields. Grating based emitters were one of the earliest surfaces shown to demonstrate coherent emission, specifically directional emission patterns [2], linear polarized emission [3], circular polarized emission [4], and short range coherence [5]. Prior publications have also noted the similarity of these surfaces to classical, resonant antennas [6], but have typically analyzed their behavior using band theory or plasmonics [7]. While promising, grating based emitters are limited in their practicality due to complexity of excitation and fundamental geometrical inflexibility.

In this paper, two frequency selective surfaces (FSS) [8] are analyzed for their potential as coherent-polarized-emission surfaces. Polarized emitting materials have been demonstrated previously in lasers and chiral materials [9]. The issue with all of these approaches is that they require non-planar structures or structures secondary to the emission surface (such as a linear polarizer) to achieve polarization. Planar infrared emission FSS (eFSS) are an excellent alternative to these surfaces and can be significantly easier to fabricate and tailor to meet specific emission needs. Similar surfaces have already been developed in the infrared for a variety of applications including spectral filtering [10], negative refraction [11], planar focusing [12], and selective absorption [13]. Specifically, an eFSS consists of an array of passive, resonant antenna elements fabricated above a ground plane. The array will emit when in physical contact with a thermal source and does not require localized excitation. The basic concepts of these surfaces are further outlined in [14]. Because eFSS require a ground plane to function, these structures do not rely on transparent substrates like many emissive diffractive grating designs [15]. This allows for direct control of the spectral emissivity independent of the surface of the thermal source. Furthermore, these surfaces enjoy the possibility of dual band operation and robust design using well-established computational electromagnetic techniques.

2. eFSS polarization theory

The emissivity of a surface can be related to its electromagnetic properties through the conservation of energy and Kirchhoff's law. The conservation of energy relates the reflectivity (ρ), transmitivity (τ), and absorptivity (α):

$$\rho(\lambda)+\tau(\lambda)+\alpha(\lambda)=1 \quad (1)$$

Kirchhoff's law for a surface at equilibrium relates the surface absorptivity to its emissivity (ε):

$$\alpha(\lambda)=\varepsilon(\lambda) \quad (2)$$

Recognizing that the eFSS requires a ground plane to function, transmitivity can be set to zero and reflectivity can be directly related to emissivity by using (1) and (2):

$$\varepsilon(\lambda)=1-\rho(\lambda) \quad (3)$$

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From (3), the spectral emissivity properties of an eFSS can be readily predicted with numerical electromagnetic modeling. Modeling using this approach has also been shown to have excellent agreement with measured spectral emissivity results [16].

One limitation to studying polarization sensitivity through simulation is that frequency-domain modeling inherently assumes a high degree of coherence in the excitation which is not present during thermal emission. Any phase values calculated by modeling for these surfaces are meaningless unless coherence is present between the randomly generated thermal current sources. Furthermore, if the eFSS element is symmetric about two or more planes and allows for orthogonal current modes to exist at resonance, then no field mechanisms are present to ensure temporal coherence between the two resonant modes, so emission from this array must be un-polarized. The lack of coherence between orthogonal current modes precludes the use of many reflective polarizer designs, such as elliptically polarized reflectarrays [17]. Instead, the only way to achieve elliptically polarized emission is to utilize a resonant element with strong cross-polarization. In this case a single thermal current can excite emission in both orthogonal linear states. The self correlation of the thermal current is sufficient to achieve ellipitically polarized emission.

It is also important to recognize that if the elements making up the eFSS are not shorted to the ground plane, they will experience some degree of coupling to neighboring elements [18]. This coupling will serve as a capacitive load and directly influences the resonance properties of the array. Given that the spectral reflection and emission performance of an FSS element are directly related, then the thermally excited currents in an emitting eFSS must also be influenced by this coupling. Thus, thermally generated currents excited on a single eFSS element will excite coherent currents on any coupled neighboring elements. Barring local defects or loss within the array that would significantly diminish coupling, spatially coherent emission should exist across a large portion of the entire structure. This distance can also be larger than what is achievable in some bulk materials where coupling is not present between all neighboring atoms.

3. Linearly polarized emission

A linearly polarized eFSS was initially developed using a dual band resonant element to verify that polarized emission using an eFSS is feasible. The simplest dual-band emitter element is the dipole microstrip patch. By ensuring the width of the dipole is small enough that it will not resonate in the same band as the dipole itself, the element will only emit linearly polarized light at its primary resonance. It should be noted that the dipole element is not the only eFSS geometry with dual-band behavior. More complicated designs could be developed depending on the spectral properties desired.

The ground plane and supporting structure for the proposed dipole structure consisted of a 380 µm thick silicon wafer with an 85 nm thick film of aluminum deposited directly on the wafer. A 1.2 µm film of Dow Corporations benzocyclobutene (BCB) was spun-on to isolate the elements from the ground plane and the eFSS elements were made of a lossy 100 nm film of titanium, to increase the bandwidth of the surface [19]. The dipole antenna elements were 2.9 µm by 0.5 µm and the square unit cell spacing was 5 µm. A schematic and SEM image of the designed dipole array is shown in Fig. 1. Modeled emissivity data, from the commercially available modeling package Ansoft Designer, is presented in Fig. 2. The modeling approach used is identical to the one developed in [16] except that the optical properties of the thin-films were fixed to their measured values at 28.3 THz. This approach is valid because of the wide spectral range of the measurement techniques employed minimizes the impact of spectral damping [19]. Only the polarization of the measured emission is of interest, not the absolute magnitude of the emission. Future studies could utilize a spectral radiometer [14] to measure the magnitude of the radiated emission.

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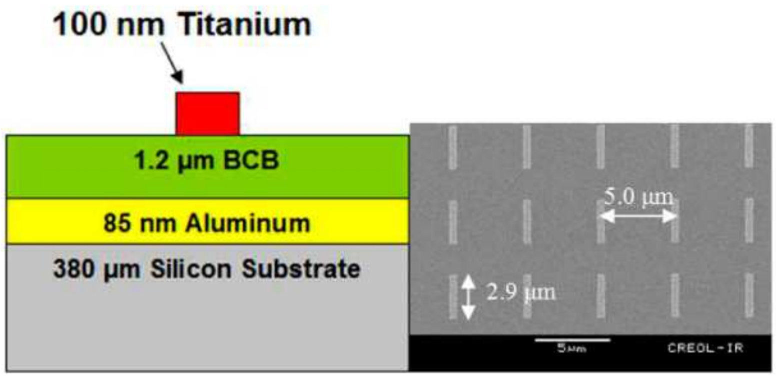

Fig. 1. Schematic of a unit cell of the dipole array and a scanning electron micrograph of the fabricated array with array dimensions labeled. The width of the dipoles is 0.5 µm.

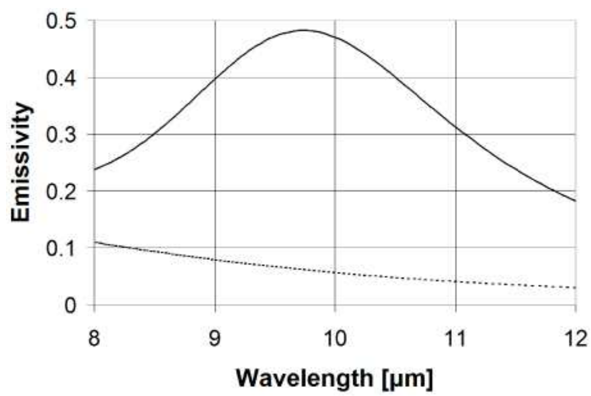

Fig. 2. Modeled emission spectrum of the microstrip dipole. The dark line is the polarization state along the length of the dipole and the dotted line is the polarization state along the width of the dipole.

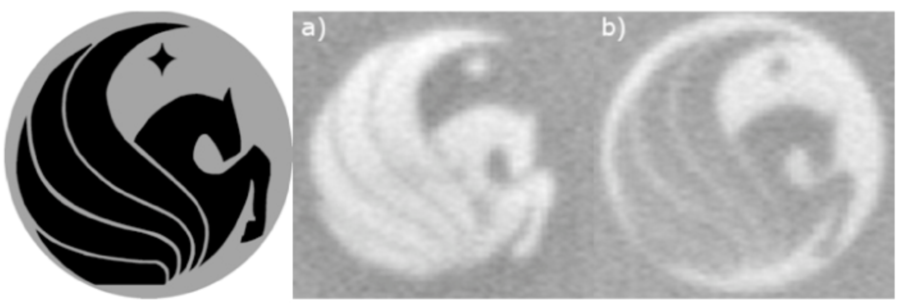

Fig. 3. Linearly polarized Pegasus (black regions correspond to vertically orientated dipoles and gray regions correspond to horizontally orientated dipoles). Thermal images of the linearly polarized Pegasus with the camera's linear polarized (a) horizontally oriented and (b) vertically oriented.

For visual verification of the linear nature of the emission surface, a pattern using the University of Central Florida's emblem, the Pegasus, was fabricated using orthogonally orientated dipoles. Fabrication of the linearly polarized eFSS was carried out using a standard electron-beam lithography process. The Pegasus was 27.5 mm in diameter. Images of this device produced using an 8-12 µm camera and a linear polarizer (Fig. 3) demonstrate the high contrast response of the dipole over a large bandwidth. When the array is imaged without a

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polarizer present in the optical train of the Pegasus both orthogonal dipoles emit equally and the emblem could not be resolved.

5. Multi-layer, circularly polarized emission

Linearly polarized emission surfaces are also one method to improve existing circularly polarized emission systems. Prior to this research, the best way to achieve circular polarized emission was to use a wire-grid to linearly polarize the emitted radiation and then use a quarter-wave plate to delay one orthogonal state of the linearly polarized radiation by 90°. In general, one would prefer an integrated thin-film solution from the points of view of robustness and efficiency. The most obvious limitation in the discrete polarizer approach is that the wire-grid polarizer will suppress half of the emitted light, greatly reducing the power of an already inefficient emission process and causing unwanted scatter and thermal loading. The wire grid, the surface closest to the emitting surface, is not resonant. This means that another coating or structured surface must be placed on the emitting surface if simultaneous control of spectral emissivity is desired. Furthermore, previous discrete designs have typically mounted the polarizer and plate on a separate substrate that cannot be easily placed in contact with the emitting surface due to structural or thermal shock reasons [15]. This leads to volumetrically large systems and limits the possibility of conformal polarization control.

All of these limitations can be overcome by replacing the wire-grid polarizer with a linearly polarized emission surface (Fig. 4). The linearly polarized surface will allow for more emitted energy in the band of interest than the wire-grid. This is because the undesired polarization emission path is not supported by the surface and all emission from the heated surface must occur in the desired polarization state only. Control of spectral emissivity is readily available by altering the geometry and metal of the eFSS. The system is also significantly more compact than the wire-grid design with the substrate of the discrete design replaced with an electrically thin, thermal insulation layer. As long as the quarter-wave plate and the linearly polarized surface do not couple, they will behave identically to the meanderline structure measured in [4].

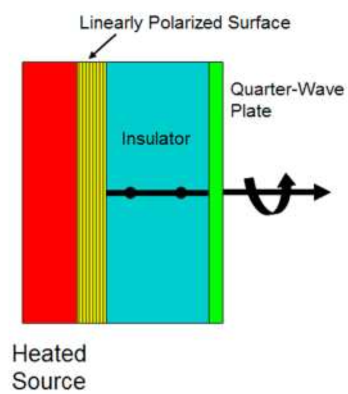

Fig. 4. Compact, multi-layer circular polarizer for emitted radiation.

6. Single element circularly polarized emission

While the multi-layer circularly polarized emission surface is an improvement over earlier designs, it is of interest to see if a planar surface that emits circularly polarized radiation can be developed using only a single element. To achieve circularly polarized emission using a planar element an asymmetric structure supporting two interacting orthogonal modes must be utilized. To that end a tripole [20] eFSS structure was adapted. The tripole was initially chosen due to its significant cross-polarization and the fact the two orthogonal polarization states share common current paths. By shortening one of the legs of tripole, it was possible to spectrally shift one resonant mode of the element resulting in a progressive phasing [21]

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between the two orthogonal linear polarization states. The length of the leg was designed to result in a phase delay of 90 degrees and minimize the difference in emissivity between the two orthogonal states. The resulting tripole exhibited circularly polarized emission over a defined spectral range. The modeled results for the asymmetric tripole with dimensions defined in Fig. 5 are presented in Fig. 6. The modeled device exhibits a large band of operation from about 8.5 to 10.8 μm. Other than the geometry of the element, all design and fabrication parameters are identical to the linearly polarized eFSS in the previous section.

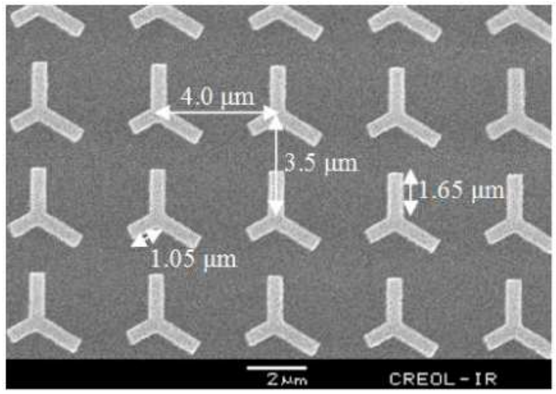

Fig. 5. Scanning electron micrograph of the fabricated asymmetric tripole array with dimensions labeled. The width of the arms are 0.5 μm.

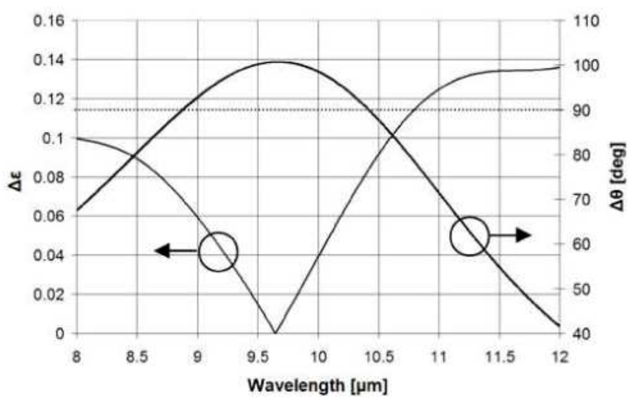

Fig. 6. Modeled emission and phase properties of the asymmetric tripole. A dotted line marks the ideal 90-degree phase difference required for circular polarized emission.

The asymmetric tripole, as shown in Fig. 5, was fabricated into a four-square checkerboard pattern with two squares having right-handed emission and the other two having left-handed emission. The piece was then mounted on a hot plate and imaged twice with a linear polarizer present. It was aligned once in the horizontal direction and once in the vertical direction. The arrays were seen to exhibit a degree of linearly polarized emission which is consistent with the model ($\Delta\varepsilon$ is not equal to zero over the entire 8 to 12 μm band). Next, a quarter-wave plate was introduced in front of the polarizer and the array was re-imaged in the two orthogonal circularly polarized states (Fig. 7). The images show that the arrays exhibit circularly polarized emission as only the quarter-wave plate was rotated when taking the pictures. A limitation in this measurement was that a meanderline polarizer [4] was used as the quarter-wave plate. While more broadband than a conventional crystal quarter-wave plate, the meanderline exhibits some chromatism and a preference towards one linear polarization state. Nevertheless, these initial results are promising and suggest the need for additional investigation and optimization.

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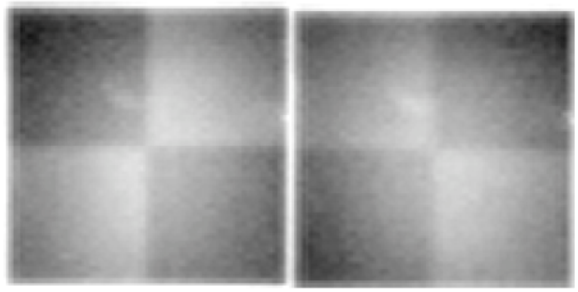

Fig. 7. Two thermal images (side by side) of checkerboard asymmetric tripole with circular polarizer in front of the camera and in two orthogonal directions.

7. Summary

Both linear and circularly polarized emission using a planar eFSS has been demonstrated for the first time. These surfaces are especially interesting due to their design flexibility and compactness when compared to similar grating based polarized emitters. The results also indicate a high degree of local coherence in emission which may be exploited to give rise to robust directional or focusing emission surfaces employing eFSS.

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