Directional Thermal Emission from a Leaky-Wave Frequency Selective Surface

*Dept. of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, 400 W. 13th St., Rolla, MO, USA 65409; bPlasmonics Inc., PO Box 6150, Orlando, FL USA 32802; cDept. of Physics and Optical Science, University of North Carolina at Charlotte, 9201 University City Blvd., Charlotte, NC USA 28223; dCREOL, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL USA 32816; eElectrical and Computer College of Engineering, Florida Institute of Technology, 150 W. University Blvd., Melbourne, FL USA 32901

ABSTRACT
We design, fabricate, and characterize a Frequency Selective Surface (FSS) with directional thermal emission and absorption for long-wave infrared wavelengths (LWIR). The FSS consists of an array of patch antennas connected by microstrips, the ensemble of which supports leaky-wave type modes with forward and backward propagating branches. The branches are designed to intersect at 9.8 μm, and have a broadside beam with 20° FWHM at this wavelength. The absorption along these branches is near unity. Measurement of the hemispherical directional reflectometer (HDR) shows good agreement with simulation. The ability to control the spectral and directional emittance/absorptance profiles of surfaces has significant applications for radiation heat transfer and sensing.

Keywords: Frequency Selective Surface, Thermal emission, Infrared, Hemispherical Directional Reflectometer.

1. INTRODUCTION
A blackbody radiates the maximum amount of thermal energy into the far-field. The spectral distribution of this radiation is given by Planck’s law and has a diffuse Lambertian profile without polarization selectivity. While real materials deviate from the blackbody response on the basis of their electromagnetic response (principally permittivity at optical and infrared wavelengths) and surface finish, but the emitted radiation remains largely isotropic and with generally only gradual variations in the spectral distribution1. These characteristics of natural surfaces result from the fact that thermal radiation is incoherent1-4.

Controlling the angular distribution of thermal radiation has potential applications related to thermophotovoltaics, solar thermal energy collection, solar thermal management, as well as defense. Controlling the angular distribution to thermal radiation requires a degree of coherence. This has been accomplished experimentally using polar materials2 and metallic gratings3 to produce very narrow angular distributions (less than 1° FWHM). This corresponds to long coherence lengths of greater than 100 μm. These designs exhibit a leaky-wave/diffractive response with the angle of emission dependent on the wavelength. However, Cruz-Cabrera et al.4 demonstrated directional emissivity near grazing angles of incidence over controlled wavelength intervals using subwavelength periodic 2D array of resonators.

Frequency Selective Surfaces (FSS) consist of sub-wavelength metal elements. Control of the geometry and material selection, allow the scattering parameters of the surface to be engineered5. This makes a FSS a type of metamaterial (a metasurface) with electromagnetic properties typically not found in nature. FSS have been used to control the spectral6-8, phase9-11, and polarization12 responses. This is often achieved via scaling established radio frequency designs to infrared wavelengths13 which has significance at infrared wavelengths because it controls the emissivity of the surface, and hence heat transfer via radiation. For example, both Ginn et al.12 and Liu et al.14 engineered the spectral emissivity of a surface, using dipole and cross elements, respectively. In these cases the angular distribution of the emitted radiation is still relatively diffuse.

Phased array antennas are another RF concept that has been scaled to the IR15-18. In these cases two or more antenna elements are connected to a load using transmission lines. These devices have been used to generate a prescribed
angular sensitivity for detectors, both thermopiles and MOM diodes. Significantly better response was reported from the diodes because of the distributed electromagnetic absorptance of the antennas and feed structure\textsuperscript{18}. 

In this paper we design, fabricate and test a FSS based on a patch antenna/microstrip phased array to create a surface with angularly dependent thermal emission/absorption. The structure supports guided leaky-wave type modes with forward and backward propagating branches coupled to TM polarized radiation. The choice of microstrip waveguides leads to significantly better propagation lengths, and hence angular selectivity compared to previous co-planar strip designs. Because of metal losses at IR wavelengths there is a distributed load throughout the FSS which differs from conventional RF design. However, after optimization we are able to demonstrate a structure with high absorptance. These experimental results show reasonable spectral/directional agreement with simulation. This work differs from previous reports because the thermal energy couples to the resonant patches and propagates along guided modes as opposed to via surface waves. This paper presents the design, fabrication procedure, along with experimental results and for the device.

2. DEVICE GEOMETRY AND FABRICATION

We designed and optimized the structure for broadside directional emission at $\lambda = 9.8$ $\mu$m. Figure 1 shows the geometry of the Frequency Selective Surface (FSS). Conceptually, it consists of a series of patch antennas ($a \times b = 2.157 \times 2.674$ $\mu$m) connected by microstrip transmission lines ($w = 0.730$ $\mu$m). The pattern is separated from an Au ground plane by a 0.650 $\mu$m standoff of ZnS. Both the antennas and the groundplane are Au, and are 75 and 150 nm thick, respectively. The structure is periodic in both the $x$- and $y$-directions ($p_x \times p_y = 4.036 \times 4.3625$ $\mu$m).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{FSS unit cell and dimensions.}
\end{figure}

ANSYS HFSS, a commercial Finite-Element Method (FEM) full-wave electromagnetic solver, was used to optimize the structure. The objective was to produce unity absorptance at $\lambda_0 = 9.8$ $\mu$m (peak emission at room temperature from Wien’s displacement law). Floquet ports were used to simulate the unit cell shown in Fig. 1 and predict the response. Ellipsometry (J.A. Woollam IR VASE) was used to experimentally measure frequency-dependent material properties were used in the electromagnetic model to increase its fidelity\textsuperscript{19}. In optimizing the design we specifically chose dimensions to minimize diffraction and Surface Plasmon Polariton (SPP) modes at the design wavelength. These occur when

$$
\lambda = \left( \pm \sin \theta_i + 1 \right) \frac{P}{m}
$$

where $p$ is periodicity, $\theta_i$ is the angle of incidence, and $m$ is the order. At LWIR wavelengths the surface plasmon has the nearly the same wavelength as free-space and the energy is not tightly bound to the surface leading to long propagation lengths.

Figure 2 shows SEM images of the fabricated surface. E-beam evaporation was used to deposit the Au ground plane on a Si substrate. The ZnS standoff was thermally evaporated on top of the ground plane. E-beam lithography lift-off was used to define the structure. The antennas were also deposited with e-beam evaporation and have a 5 nm thick Cr adhesion layer (not included in simulation). We patterned a 2×2 cm structure using lift-off and e-beam lithography. The...
relatively large area was required to measure the far-field using a hemispherical directional reflectometer (HDR). The vast majority of the sample yielded structures that matched the design, however, there are areas where the lift-off procedure was incomplete or became attached to the surface and is one source of discrepancy between the experiment and simulation.

![SEM images of FSS](image)

Figure 2. SEM images of FSS.

### 3. MEAUREMENTS

Figures 3 and 4 show the simulated and measured emittance, $\varepsilon(\lambda, \theta, \varphi)$. Because of the ground-plane there is no transmittance through the sample, Kirchhoff’s law gives:

$$\varepsilon(\lambda, \theta, \varphi) = \alpha(\lambda, \theta, \varphi) = 1 - \rho(\lambda, \theta, \varphi)$$

where $\alpha$ is the absorptance and $\rho$ is the measured reflectance.

Previous experimental studies directly measuring the emitted power have demonstrated this analysis to be valid for similar structured surfaces. A SOC-100 (Surface Optics: San Diego) hemispherical directional reflectometer was used to measure the reflectance. This uses an incoherent source to illuminate a gold coated hemisphere, which then focuses the radiation towards the sample at a solid angle of $2\pi$, illuminating the sample isotropically. The reflected light can then be collected at any polar angle between $\sim10$ to $80^\circ$. Figures 3 shows the simulated and measured emittance as a function of wavelength, polar angle, and azimuthal angle, $\varepsilon(\lambda, \theta, \varphi)$. Qualitatively there is reasonable agreement between simulation and measurement; although some of the peaks are shifted slightly, the principal features predicted by the model can be observed experimentally. Unfortunately optical components used in the measurement apparatus limit the HDR from taking data at normal incidence.

This structure forms a leaky-wave supports both a backward and forward propagating branches. At broadside, where these branches intersect, beam is $20^\circ$ FWHM. The reflectance is measured with a hemispherical directional reflectometer. Of note is the Fano-type interference between the forward propagating mode and a patch resonance at $\theta=35^\circ$ $\lambda=8$ $\mu$m in Fig. 3(a) which is evident in both simulation and experiment.

Figure 4 shows a comparison between measured and simulated angular emittance at discrete wavelengths for TM polarization. The figure shows that the array couples light off axis for the backward propagating leaky-wave branch for wavelengths greater than the broadside wavelength.
Figure 3. Comparison between HFSS simulated (top row) and HDR experimentally measured (bottom row) spectral/directional emittance. (a) $\varphi = 0^\circ$ TM, (b) $\varphi = 0^\circ$ TE, (c) $\varphi = 90^\circ$ TM and (d) $\varphi = 90^\circ$ TE.

Figure 4. Angular absorptance at three different wavelengths for backward propagating branch, solid lines indicate HFSS simulation and points are measured data.

The experiment validates the simulation enough that we can use the numerical model to understand the modal structure that produces the directional hemispherical emittance. The leaky-wave mode is evident in Fig. 3a. This mode is forward propagating for shorter wavelengths (ii) and backward propagating for longer wavelengths (iii). Figure 5 shows the field distributions on the $xz$ plane for points on these branches and where they converge to form a single beam (point i in Fig. 3a and 3d). This mode is also excited at under TE illumination with $\varphi = 90^\circ$. The broad angular independent mode in the TE plots $\sim 14 \mu m$ corresponds to the patch mode of the structure polarized in the y-direction (iv). Because the patches are not connected with microstrips in this direction there is significantly lower coupling and no coherence which does not give rise to an angular dependence. Figure 5 also shows the 2nd patch quadrupole mode which is sensitive to wavelength but not polarization (the v branch is visible for the TE illumination conditions in Fig. 3b and 3d). Because of symmetry, the quadrupole mode is not excited at normal incidence.
To illustrate how a thermally generated electric current can couple to the structure, we also modeled the simulation with a local excitation. Figure 6 shows the system when it is driven by a local current source. The current source is 500 nm long and centered on a patch. It is oscillating at 30.84 THz (9.72 μm). Figures 6a and 6b show the electric field in the z direction 5 nm above the patches when the current is in the x- and y-directions, respectively. Figures 6c and 6d show the far-field patterns for the antenna system, respectively. When the current is polarized in the x-direction the energy is coupled along the microstrips to multiple patch antennas. This results in a much larger effective aperture for the antenna than a single patch, producing a fan-shaped beam in agreement with Fig. 3. When the current is polarized in the y-direction there is minimal coupling the adjacent patches which produces a more isotropic far-field pattern.

4. CONCLUSION

This letter demonstrated directional thermal emission emanating from enhanced coherence provided by waveguide modes. The ability to control the spectral and directional emittance profiles of surfaces has significant applications for radiation heat transfer and sensing. The patch antennas that form the basis of this work are relatively broadband. Further selectivity can be achieved by using narrowband antennas. This work was conducted at room temperature but can be extended to systems that can efficiently radiate energy at temperatures more applicable to heat-transfer applications.
Figure 6. LW-FSS excited by a local current source. $E_z$ for current excitation in the (a) x-direction (b) y-direction. Far-field pattern for current excitation in the (c) x-direction and (d) y-direction.

REFERENCES


