SAND2008-1258C

Tailored Surfaces for Managing Thermal Emission: Plasmon/Photon Coupling Using Diffractive Optics Technology

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ABSTRACT

We present simulations and measurements of a technology that can manipulate thermal angular and wavelength emission. This work is representative of Sandia National Laboratories' efforts to investigate advanced technologies that are not currently accessible for reasons such as risk, cost, or limited availability. The goal of this project is to demonstrate a passive thermal emission management surface that can tailor the direction of emission as well as the wavelength bands of emission.

This new proposed technology enables thermal emission pattern management by structuring the surface. This structuring may be in either the lateral or depth dimension. A lateral structuring consists of a shallow grating on a metal surface. This air/metal interface allows photon/plasmon coupling, which has been shown to coherently and preferentially emit at certain wavelengths.

Keywords: Emission, absorption, plasmons, diffractive, subwavelength, gratings, infrared

1. INTRODUCTION

Any material radiates energy, which is a function of its temperature, and so can be called a thermal source. A thermal source is typically viewed as noise to be eliminated; but this emission is difficult to manage as it is incoherent and quasi-isotropic with radiation exiting the surface at every angle, as in Figure 1a). The radiation pattern emitted by the surface is broadband, Lambertian, and not easily directed. If the thermal radiation was instead coherent, then the angular emission could be directed into desirable lobes, as in antenna patterns, allowing control of the largely infrared (IR) emission, see Figure 1b). Structuring a surface on the same scale as the emitted wavelength or surface-plasmon coherence length at a metal/dielectric interface should enable us to propagate near-field, coherent effects into the far-field. A lateral structuring consists of a shallow grating on a metal surface. This air/metal interface allows photon/plasmon coupling, which has also been shown to coherently and preferentially emit at certain wavelengths.

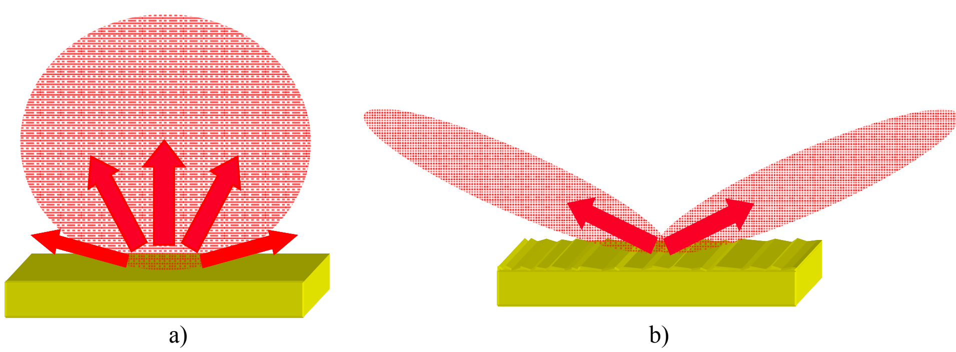


Figure 1 a) Typical Lambertian angular emission, b) directed thermal emission due to surface structuring.

The goal of this work is to identify and optimize the dominant photon coupling configuration that enables thermal radiation, emitted by a surface, to propagate as a tailored spectrum with angular directivity. We present surface structuring designs and simulations that demonstrate a passive thermal emission management surface that could influence a variety of applications, such as passive microsystem heat sinks/sources for effective directional radiation through spectral windows.

2. PLASMONS AND COUPLING MECHANISMS

Surface structuring, in the form of a grating may be etched, or deposited, onto a metal, as in Figure 2. Emission from a textured surface may be altered by utilizing the coupling of surface plasmon modes to photons via the grating. The coupling interactions between photons and surface plasmons are dependent upon the refractive index and the depth, shape, and period of the grating etched into the metal surface. These parameters provide a multidimensional search space over which to optimize a surface for a desired emission wavelength.

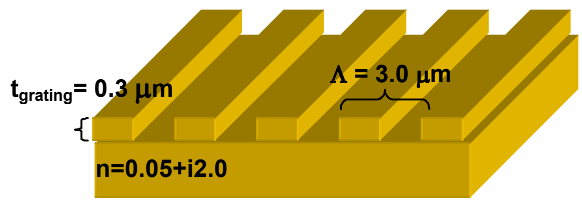


Figure 2 Grating configuration for a phantom material with complex refractive index 0.05+2.0i, with a 3 micron period and a 0.3 micron grating depth.

Figure 3 shows an example of the emission spectra for the working metal surface in Figure 2 with simple rectangular gratings etched into the surface. Since this sample is optically thick and thus has no transmitted signal, the measured absorbed signal, A = 1-Measured Reflected Signal. By Kirchhoff's Law, the absorption is equivalent to the emission, and this is the simulation shown in Figure 3, as a function of both incidence angle and wavelength. There are strong, vertical emission features indicating a large emission at a given wavelength over the entire angular band. In Figure 3, we note a strong emission peak at very high angles in the 6 to 7 micron wavelength range. This feature is very unusual as most surfaces have low emission at high angles.

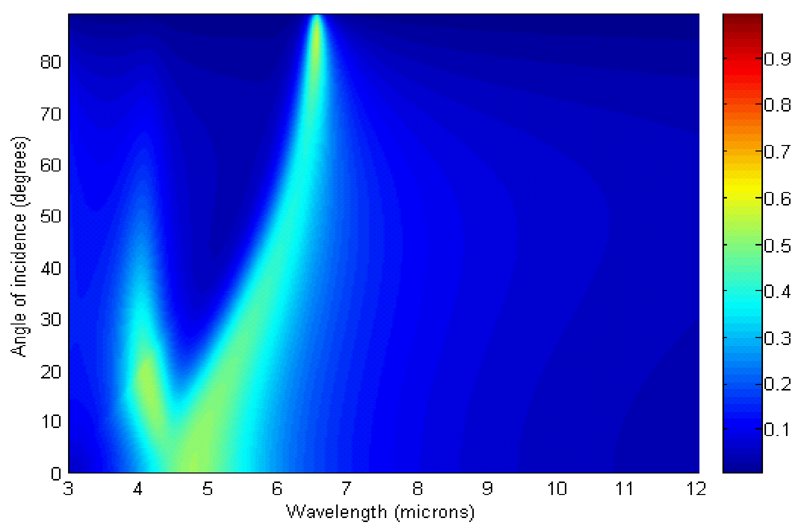


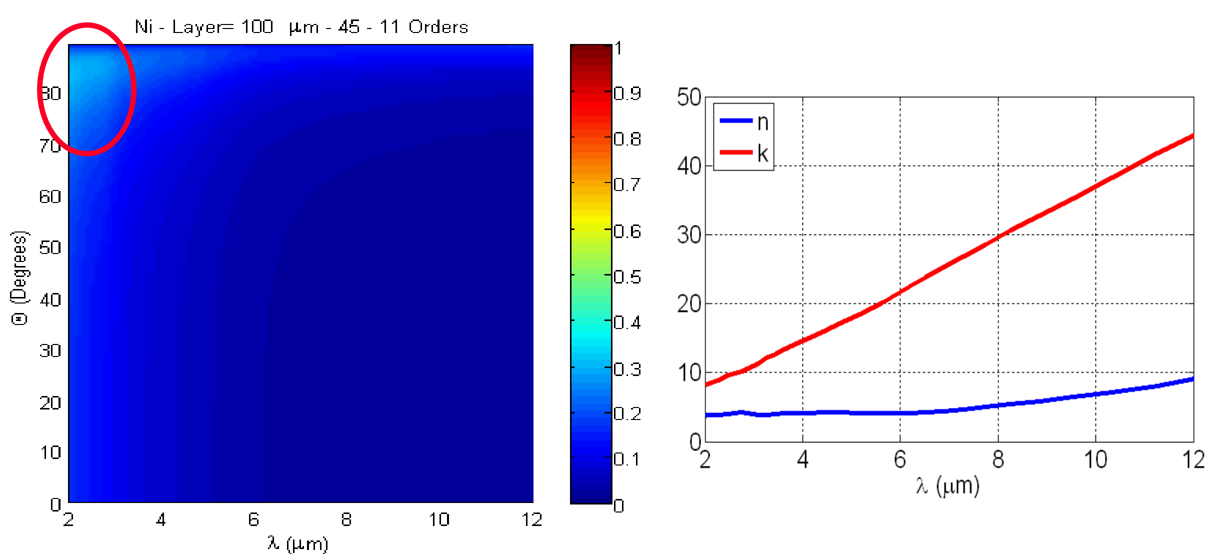
Figure 3 Emissivity simulation of a phantom metal surface with a refractive index of 0.05+2.0i and a grating period of 3 microns. The grating depth is 0.3 microns.

We and others[1] have predicted and modeled this effect with coherent, infinite-extent planewave inputs using Rigorous Coupled Wave Analysis (RCWA). This alone is not a compelling argument for far-field, coherent effects from thermal, incoherent sources since the fundamental incoherent-to-coherent connection is not modeled, but assumed. However, there are also published experiments[2] that indicate a measurable coherent response in the far-field. The hypothesis is that coherent thermal emission can occur if two conditions are satisfied: 1) a material can support a surface-plasmon polariton (for metals) or a surface-phonon polariton (for polar materials), and 2) there is a mechanism, such as a grating, to couple these surface plasmons to photons. The missing link in these works[3-4] that we hope to provide, is an unambiguous connection between high-quality fabrication and experimental measurement and the expected plasmon/photon coupling mechanism.

3. DESIGN PROCESS AND CANDIDATE CONFIGURATIONS

In our design process, we search for three material and grating phenomena to occur simultaneously: 1) bulk material absorption, especially at large, glancing angles, 2) a Wood's Anomaly, when a diffractive order becomes evanescent and its energy is absorbed by the material, and 3) absorption that appears close to the Wood's Anomaly. Plasmon/photon coupling is most effective when the plasmon's characteristic length is many times the grating period. We have found that the desired bulk material absorption happens in materials with a particular range of real and imaginary parts of the refractive index, n and k. Specifically, this occurs when $0.5 < n/k < 4$ and their magnitudes do not exceed 10.

Figure 4a) shows a real material, bulk nickel, with absorption (and consequently emission) in the two to three micron region. This is consistent with optimal refractive index combinations in the two to three micron region, as seen in Figure 4b). We are most interested in emphasizing emission at the higher angles of exitance (the region circled in Figure 4a). Here, near-normal emission is low, but it is significant at glancing angles greater than 80 degrees (i.e., nearly parallel to the nickel surface).



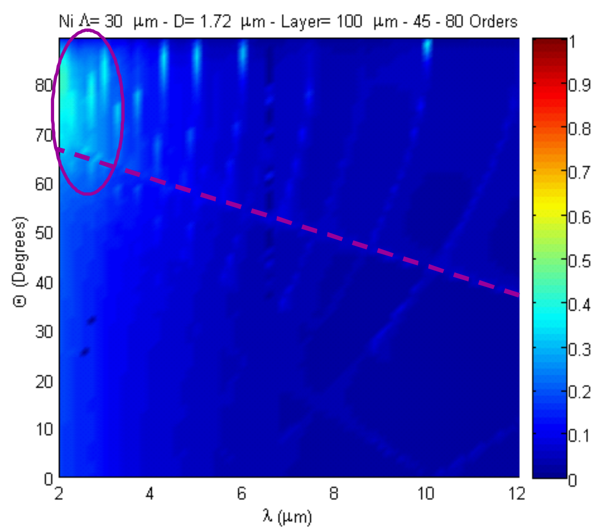
a) b)

Figure 4 a) Absorption (or, equivalently, emission) of bulk nickel as a function of incident wavelength and incident angle, and b) the real (n) and the imaginary (k) parts of the refractive index for nickel as a function of wavelength.

4. GRATING SELECTIONS WITH WOOD'S ANOMALIES

When a grating is added to a material's surface, the reflection is no longer a continuous one as a function of angle. Instead, discrete diffraction occurs which has only certain, allowed angles. Thus, light can only reflect or transmit at specific angles (and specific wavelengths), and these orders depend upon the grating material refractive index, the grating period, and the grating depth. For a given incident wavelength and incident angle, there will be several diffracted orders, which are symmetrical about the specular, reflected order if the incident angle is zero degrees (normal incidence). In this configuration, as the wavelength is increased, the orders begin to spread in angle and move nearer the surface of the material.

At some wavelength/angle-of-incidence combination, a reflected order will reach 90 degrees (become parallel to the surface), at which point it becomes evanescent and no longer propagates energy away. For dielectrics, with no absorption, this energy is redistributed among the remaining transmitted and reflected orders. However for thicker, absorbing metals, this energy cannot be transmitted. For some fortuitous grating configurations, this energy is absorbed by the metal and converted to a surface-plasmon polariton. We can predict the optimal grating and material combinations that support an efficient photon/plasmon conversion with RCWA simulations as in Figure 5. The absorption of an incident plane wave on nickel, with an added grating, is shown in Figure 5 as a function of both angle of incidence and wavelength. A Wood's Anomaly is evident as a linear feature that starts at a wavelength equal to the grating's period, for normal incidence, and continues at greater angles of incidence for lesser and greater wavelengths. Thus, along this linear feature, the wavelength/angle combination produces a diffractive order that just goes evanescent and is absorbed (converted to a plasmon). The encircled region in Figure 5 shows increased absorption (and equivalently, emission) at angles above the Wood's Anomaly linear feature. We are concentrating our efforts in these angular regions.



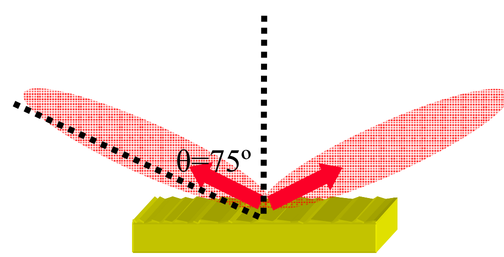


Figure 5 Simulation of absorption of an incident plane wave on nickel, with an added grating, as a function of both angle of incidence and wavelength for a 1.72 micron thick grating with a 30 micron grating period. A Wood's Anomaly is evident as a linear feature that starts at a wavelength equal to the grating's period (indicated by the dotted line), for normal incidence, and continues at greater angles of incidence for lesser and greater wavelengths. A region of enhanced absorption (and equivalently, emission) due to the grating coupling is encircled.

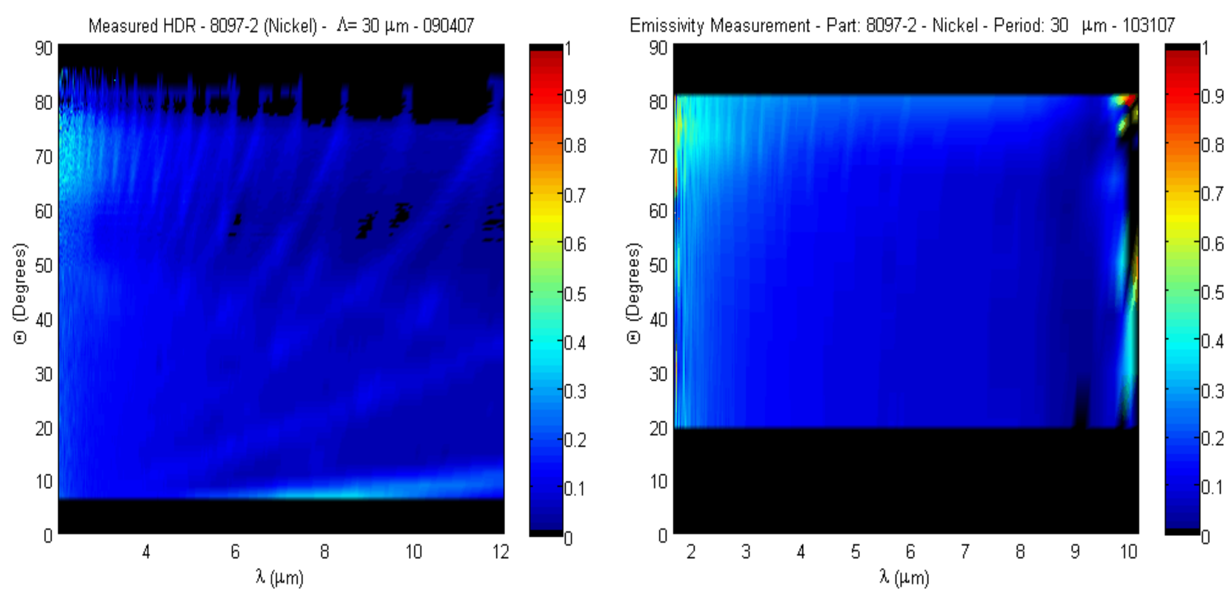
5. EMISSION MEASUREMENTS

We realized the above design in nickel with a 30 micron grating and characterized the device response using two different techniques. First we measured the hemispherical directional reflectivity of the sample using an SOC-

100. The measurement with the HDR is identical, by reciprocity theorem, to the directional hemispherical reflectance (DHR)[5]. The output of the tool is directed to a FTIR that is setup from 2 to 25 microns. The HDR uses a blackbody at 973 K to diffusely illuminate the part. The illumination is done using a 2π imaging hemi-ellipsoid, where the blackbody is located at one of its foci and the sample in the other. Light reflected from the part is collected by a movable overhead mirror and collimated into the FTIR. The measurement is done in a nitrogen-purged environment. The HDR has a cold shield around the blackbody to eliminate direct illumination of the sample. For every incident angle, the HDR performs 32 scans and interleaves them with 32 scans that had the blackbody blocked. The second set of scans is used to subtract unwanted signal from the part. The measurements were done between 8 and 80 degrees of incidence, using steps of 2 degrees. Since this sample is optically thick and thus has no transmitted signal, the measured absorbed signal, A = 1-Measured Reflected Signal. By Kirchhoff's Law, the absorption is equivalent to the emission, and this is the measurement shown in Figure 6a), as a function of both incidence angle and wavelength.

In addition, we directly measured the emission (see Figure 6b) from the nickel sample. The part was tested using an in-house, variable-angle, directional emissometer. The output of the tool is directed into an FTIR that can take data across the 2 to 25 micron range. To perform the measurement the sample is placed in a vacuum and heated to 533 K. The testing setup has a cold shield to reduce thermal background noise and reflected light from the sample. The signal emitted by the sample at 2.5 microns is small. To improve the measurement at this wavelength we averaged 256 scans per angle. We accessed emission angles from 20 to 80 degrees. The resolution was: 10 degree steps in the 20 to 60 degree range, 5 degree steps in the 60 to 70 degree range, and 2.5 degree steps in the final 70 to 80 degree range.

Both of these results in Figure 6 map well with our predictions in Figure 5. Clearly the bulk emission at angles greater than 70 degrees is enhanced due to the applied grating. Measured data could not be collected at angles greater than 75 degrees for the HDR and 80 degrees for the emissometer, but the trend to enhanced emission at these higher angles is consistent with prediction.

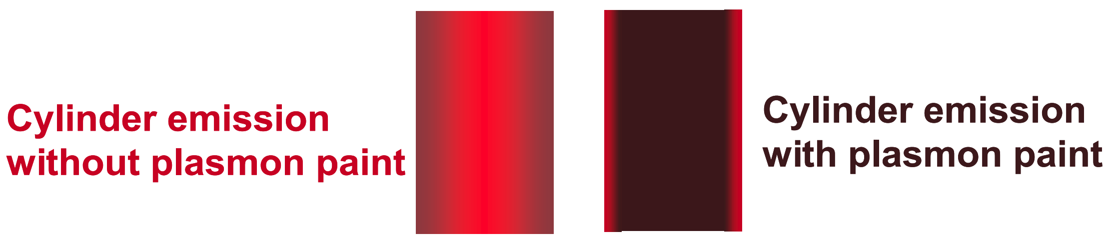


a) b)

Figure 6 a) shows Emission = 1-Reflected Signal, and b) direct emission measurements as a function of both angle of exitance and wavelength for a 30 micron period and 1.72 micron deep grating in nickel.

6. PLASMON PAINT IMPLEMENTATION

The underlying physics of this technology gives us a practical, realistic path to implementation – paint with imbedded chips. Plasmons have a relatively short characteristic length, on the order of 100 microns. Because of this, the paint chips need be not much longer than this. We plan to fabricate these tiny, flat elements and disperse them in a liquid that can be conformally applied, like paint. Figure 7a) shows a schematic picture of a cylinder with Lambertian emission. The brightest intensity in the IR is around normal exitance and falls off as the cylinder face curves away from the viewer. Figure 7b) illustrates the same cylinder with plasmon paint applied.



a) b)

Figure 7 Illustration of predicted thermal emission distribution from a) an "unpainted" cylinder with typical Lambertian emission, and b) a cylinder coated with plasmon/photon coupling paint chips.

7. CONCLUSIONS

We presented simulations and measurements of a technology that can manipulate thermal angular and wavelength emission. This work is representative of Sandia National Laboratories' efforts to investigate advanced technologies that are not currently accessible for reasons such as risk, cost, or limited availability. The goal of this project is to demonstrate a passive thermal emission management surface that can tailor the direction of emission as well as the wavelength bands of emission. Applications for such a technology are numerous in the recent literature[6-9].

This new proposed technology enables thermal emission pattern management by structuring the surface. This structuring may be in either the lateral or depth dimension. A lateral structuring consists of a shallow grating on a metal surface. This air/metal interface allows photon/plasmon coupling, which has been shown to coherently and preferentially emit at certain wavelengths.

We described a design process for identifying material and grating configurations for optimal plasmon/photon coupling. Specifically, three phenomena should be present: 1) bulk material absorption at large, glancing angles, 2) a Wood's Anomaly, and 3) absorption that appears close to the Wood's Anomaly. Moreover, we found that the desired bulk material absorption happens in materials with a particular range of real and imaginary parts of the refractive index, n and k. This occurs when $0.5 < n/k < 4$ and their magnitudes do not exceed 10.

Using this design process, we examined nickel and a large-period grating configuration that produces enhanced, directed emission within specific wavelength regions, particularly at grazing angles. Simulations as well as measurements confirmed that this configuration can preferentially emit a selected waveband of radiation into large angles. This feature is unusual as most surfaces have low emission at high angles.

Finally, we outlined a practical and realistic method for implementing this technology – plasmon paint. This simple method of application is a direct consequence of the fundamental plasmon/photon coupling physics.

ACKNOWLEDGMENT

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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