



Managing Thermal Emission: Subwavelength Diffractive Optics Technology in Support of SOF

LDRD Day

Sept. 19, 2007

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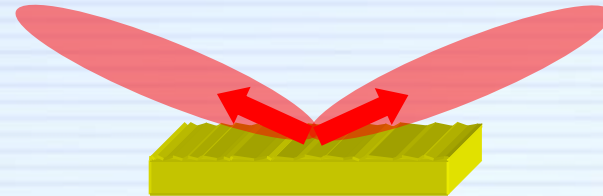
Shanalyn A. Kemme, A.A. Cruz-Cabrera, D.W. Peters
Photonic Microsystems Technologies, Org 01725



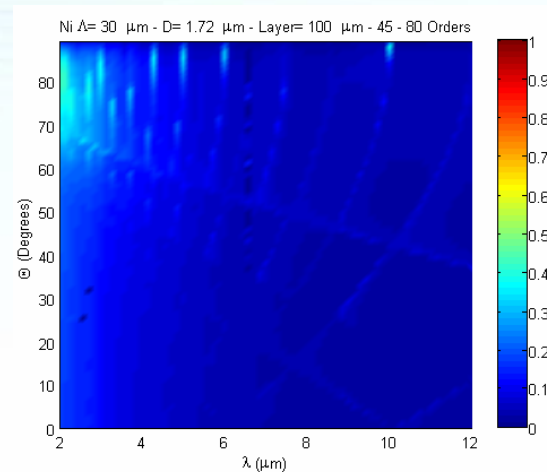


Outline

- Concept
- Some Applications
- Hypothesis
- Design Process
- Material Selection
- Wood's Anomaly
- Measurements
- Implementation



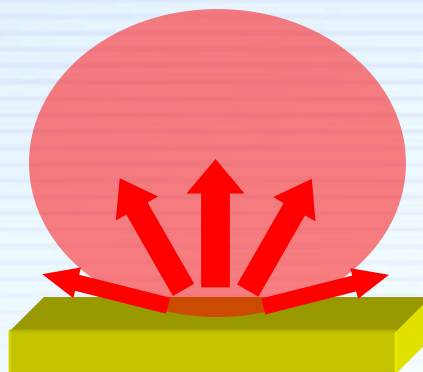
$$\varepsilon'_{\lambda}(\lambda, \beta, \theta, T) = \alpha'_{\lambda}(\lambda, \beta, \theta, T)$$



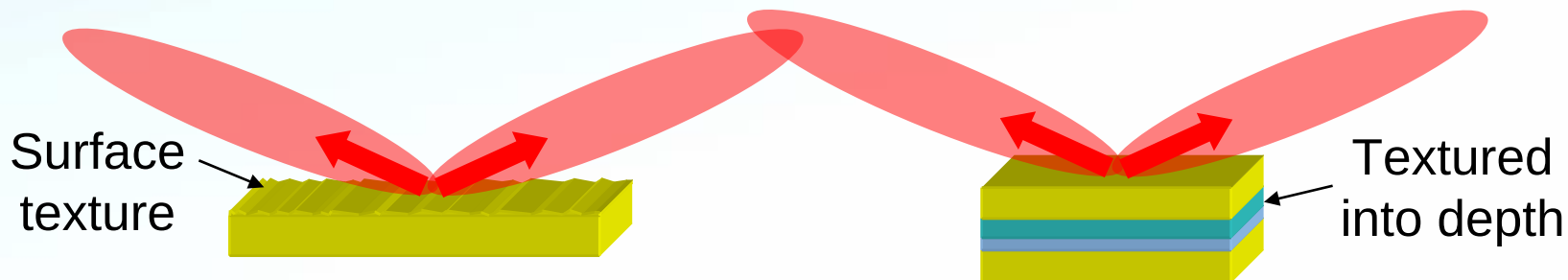


Coherent Thermal Emission Through Photonics/Plasmonics

A uniform surface has emission that is Lambertian: light is emitted in all directions



Adding texture to a surface can lead to coherent, and consequently, directed emission with wavelength selectivity



Combination of the two effects is currently unexplored

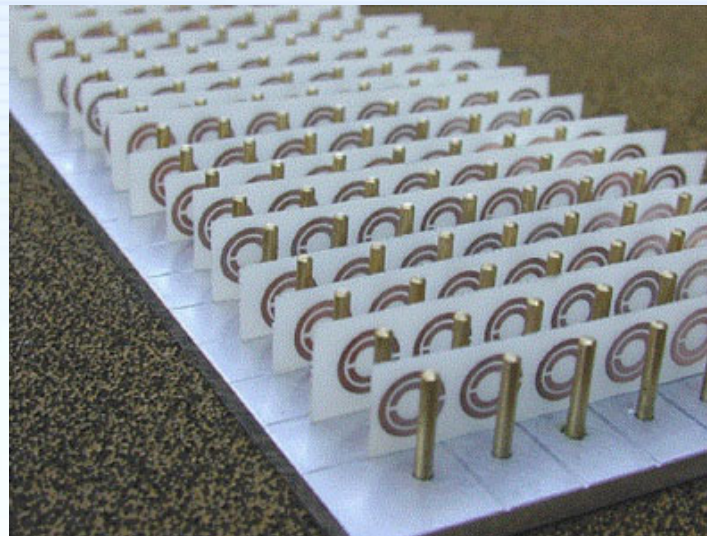


In the News, But Not What We Are Doing

A Real Invisibility Cloak

The Pentagon Funded A Study Into Stealth Technology Straight Out Of The 'Harry Potter' Books
WASHINGTON, May 25, 2006

John Pendry
Imperial College London



$$T + R + A = 1$$

- Pendry's project modifies the **reflection** of incident light.
- We are modifying the **emission/absorption** of light.



Why Does Sandia Care?

Applications:

- Thermal emission mitigation
- Microsystem passive heat sinking/sourcing management

New science:

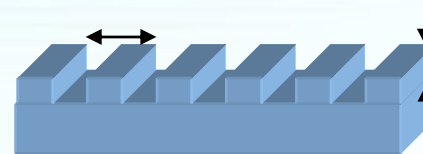
- Quantify and Optimize Plasmon/Photon coupling through materials and configurations
- Capitalize on emerging technology through Sandia's world-class fabrication facility and numerical capabilities



Hypothesis

Coherent thermal emission can occur if we have at least these two conditions:

- A material can support a surface-plasmon polariton (for metals) or a surface-phonon polariton excitation (for polar materials).
- There is a mechanism (a grating) to couple the surface plasmons to photons.



1. M. Laroche, C. Arnold, F. Marquier, R. Carminati, and J.-J. Greffet, S. Collin, N. Bardou, and J.-L. Pelouard, "Highly directional radiation generated by a tungsten thermal source" Opt. Lett., 30, 2623-2625, 2005.
2. F. Ghmari, T. Ghbara, M. Laroche, R. Carminatti and J.-J. Greffet, "Influence of microroughness on emissivity," J. Appl. Phys, 96, 2656-2664, 2004.
3. J.-J. Greffet, R. Carminati, K. Joulain, J.-P. Mulet, S. Mainguy & Y. Chen, "Coherent emission of light by thermal sources," Nature, 416, 61-64, 2002.



Applications in the Literature

Thermophotovoltaics: enhance the efficiency of infrared photovoltaic cells and solar absorbers

- M. Laroche, R. Carminati, and J.-J. Greffet, “Coherent Thermal Antenna Using a Photonic Crystal Slab,” Phys. Rev. Lett., 96, 123903(1-4), (2006).
- H. Sai, Y. Kanamori and H. Yugami, “Tuning of the thermal radiation spectrum in the near-infrared region by metallic surface microstructures,” J. Michromech. Microeng., 15, S243–S249, (2005).

Radiative cooling of semiconductor devices & efficient infrared light sources

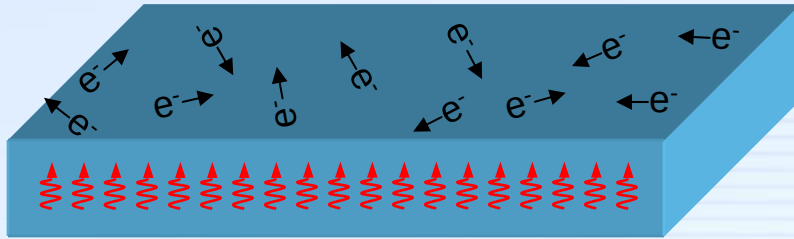
- F. Marquier, K. Joulain, J.P. Mulet, R. Carminati, J.-J. Greffet, “Engineering infrared emission properties of silicon in the near field and the far field,” Opt. Comm., 237, 379–388, (2004).

High-efficiency incandescent lamps

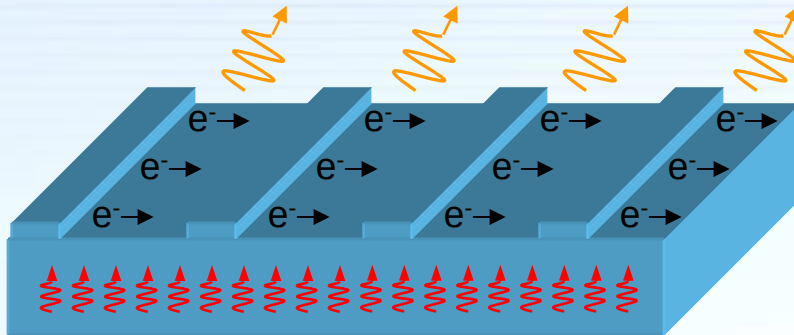
- H. Sai, H. Yugami, Y. Akiyama, Y. Kanamori, and K. Hane, “Spectral control of thermal emission by periodic microstructured surfaces in the near-infrared region,” J. Opt. Soc. Am. A, 18, 1471-1476,(2001).



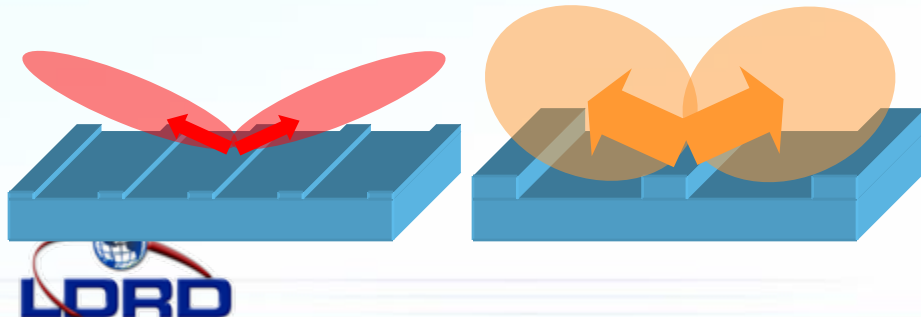
Physical Mechanisms



Thermal energy excites surface plasmons on the material.



A grating in the material provides phased coupling between the plasmons and emitted photons.



The grating parameters determine the angular and wavelength “shape” of emission.



Theory & Hypothesis

- Kirchhoff' Law:

$$\varepsilon'_{\lambda}(\lambda, \beta, \theta, T) = \alpha'_{\lambda}(\lambda, \beta, \theta, T)$$

Where ε'_{λ} is the directional spectral emissivity and α is the directional spectral absorptivity. λ is the spectral dependence, β and θ are the angular dependences and T is the temperature.

R. Siegel and J. R. Howell "Radiation Heat Transfer: The Blackbody, Electromagnetic Theory, and Material Properties," NASA SP-164, Lewis Research Center (1968)



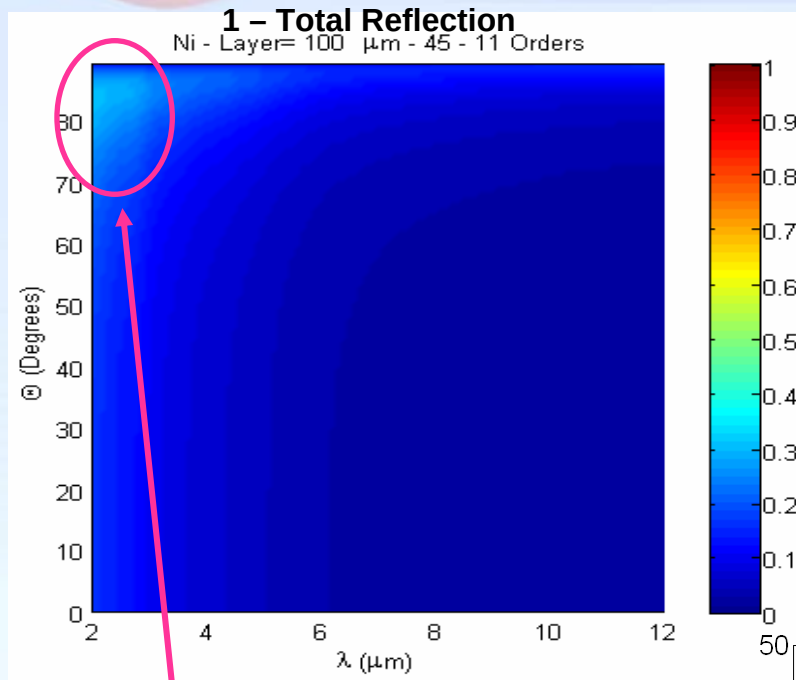
Our Design Process

To design a device we look for the convergence of these things:

- Material Selection: **absorption** in a bulk material at **large, glancing angles**. This happens in materials where $0.5 < n/k < 2$ and their magnitudes do not exceed 10.
- A **Wood's Anomaly**: when a diffractive order becomes evanescent and its energy is absorbed by the material (instead of transferring to other existing orders).
- A **Surface-Plasmon Polariton** (SPP) appears close to the Wood's Anomaly. It is most effective when its characteristic length is many times the grating period.

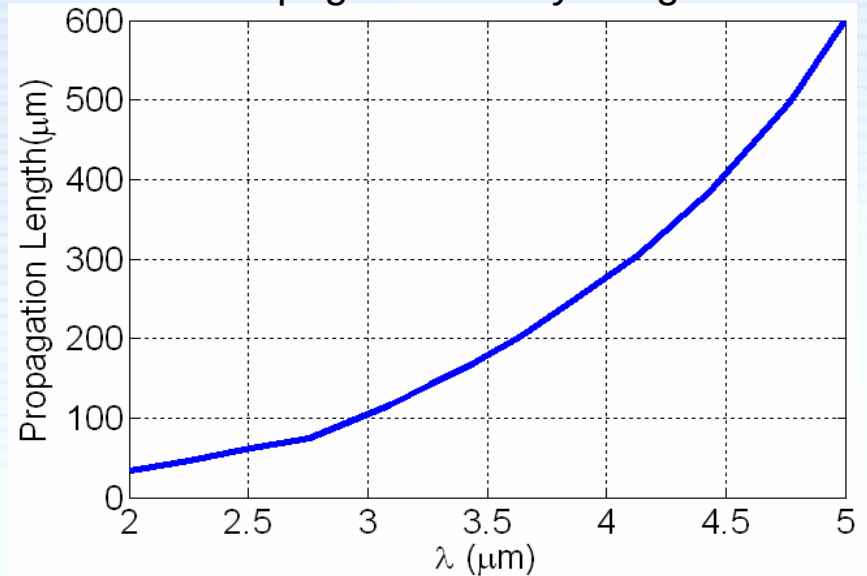


Material Selection - Nickel

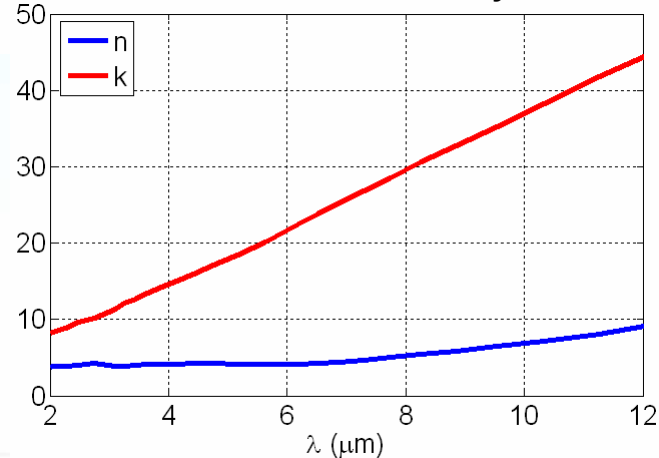


- Long decay length
- Practical sampling with grating period
- High absorption

Propagation Decay Length



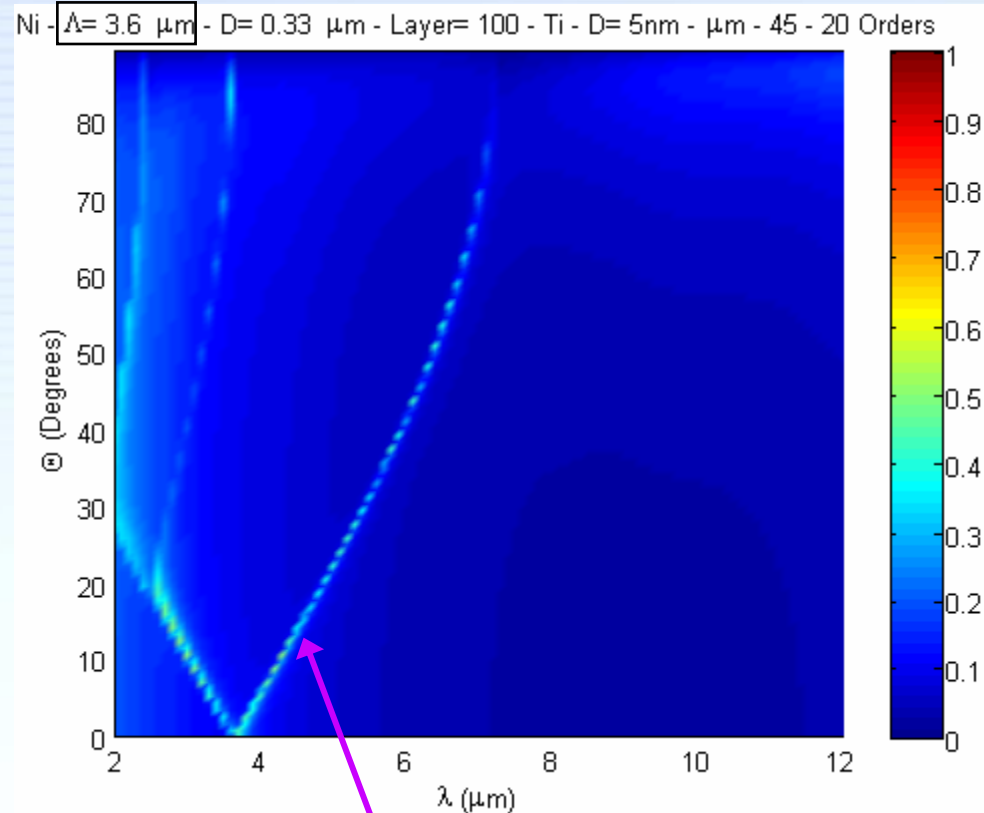
Relative Permittivity





Wood's Anomaly - Nickel

1 – Total Reflection

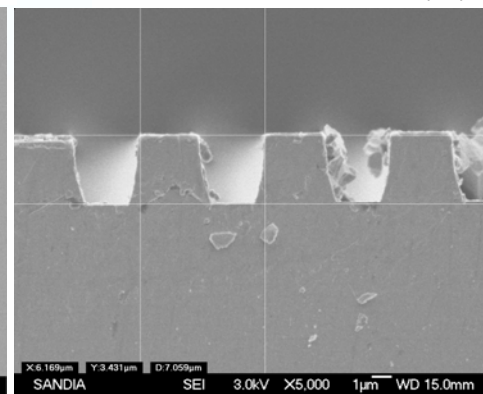
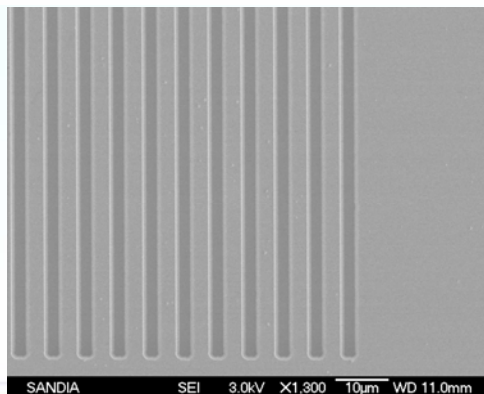
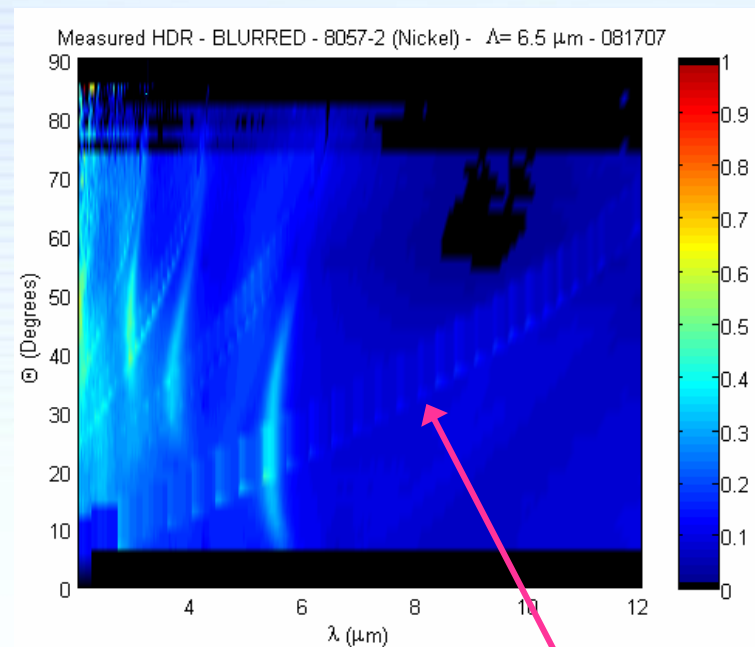
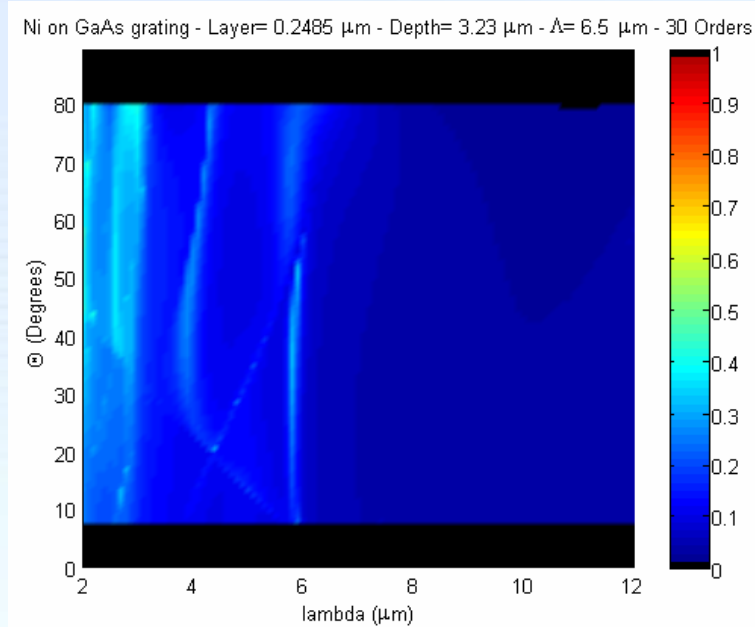


Wood's
Anomaly



Simulation and Measurement : Nickel with Small Grating Period

Simulation : 1 – Total Reflection **Measurement** = 1 – Total Reflection

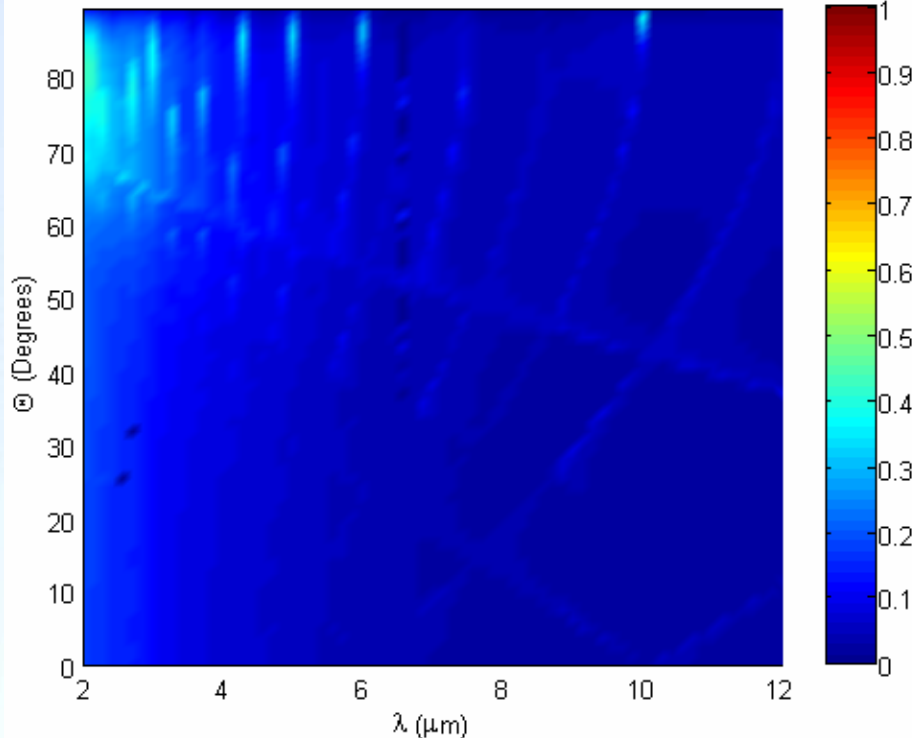




Simulation and Measurement: Nickel with Large Grating Period, High-Angle Emission

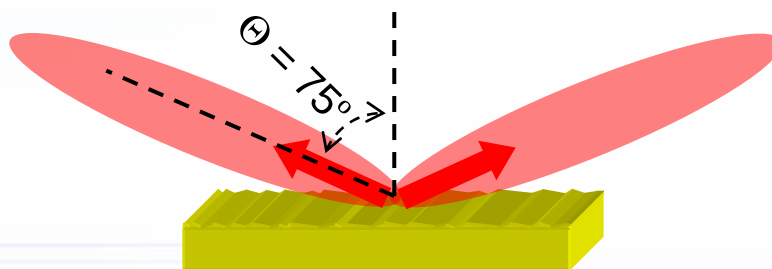
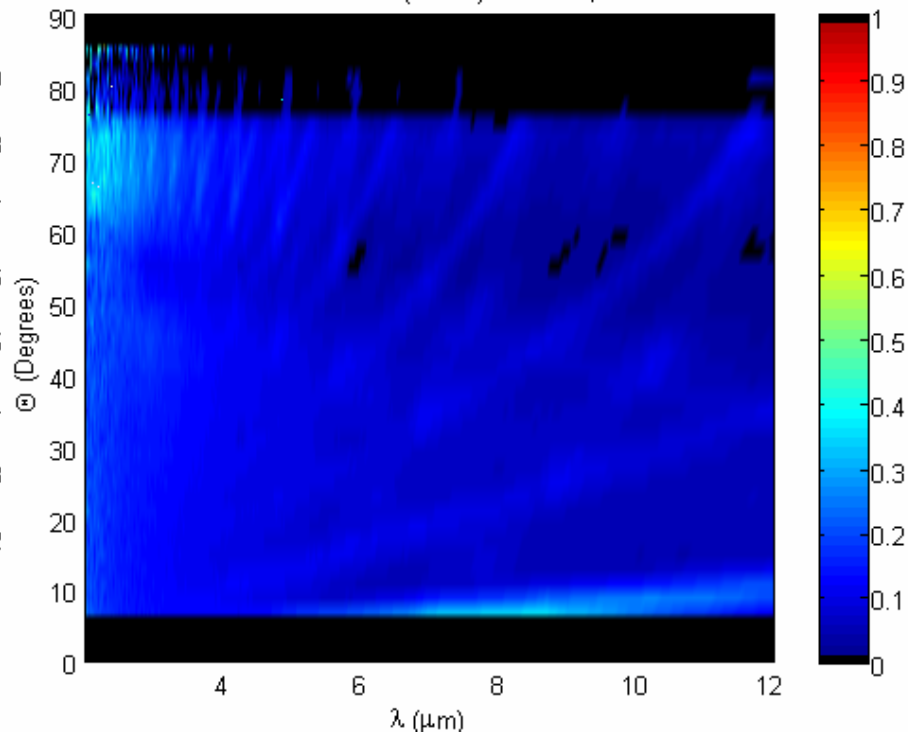
Simulation of $\Lambda=30\mu\text{m}$ on Ni

Ni $\Lambda=30\ \mu\text{m}$ - $D=1.72\ \mu\text{m}$ - Layer= 100 μm - 45 - 80 Orders



Measurement of $\Lambda=30\mu\text{m}$ on Ni

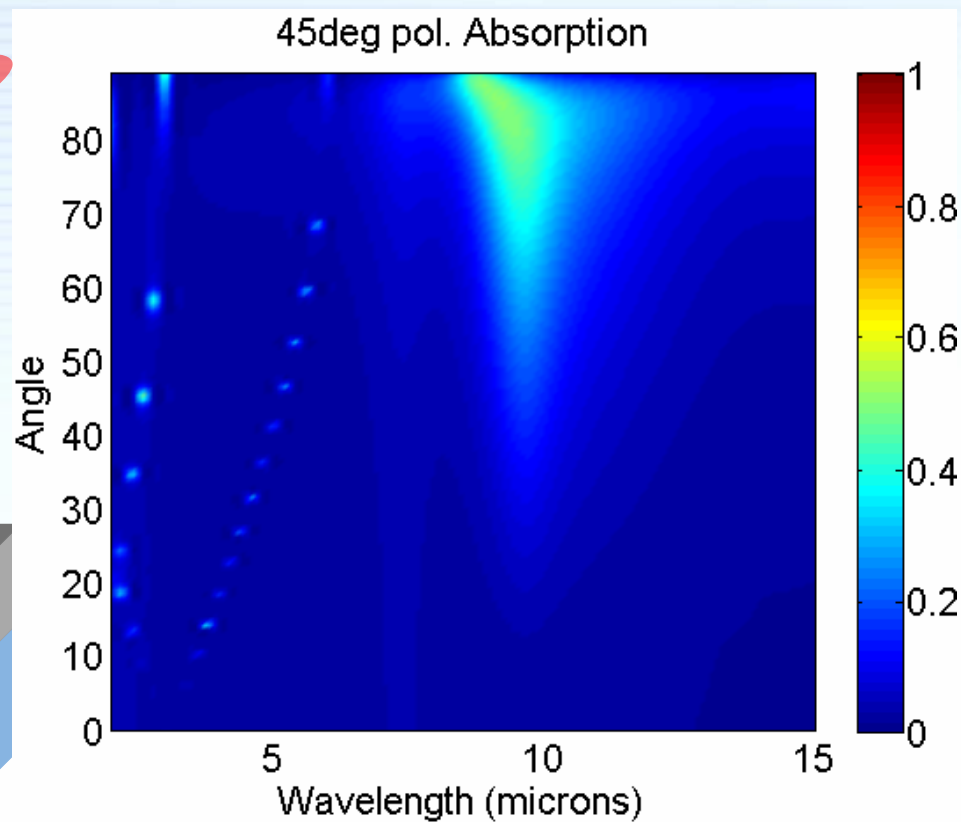
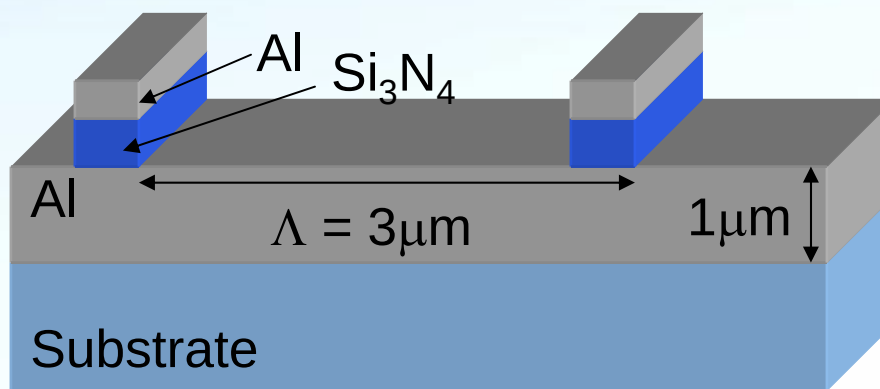
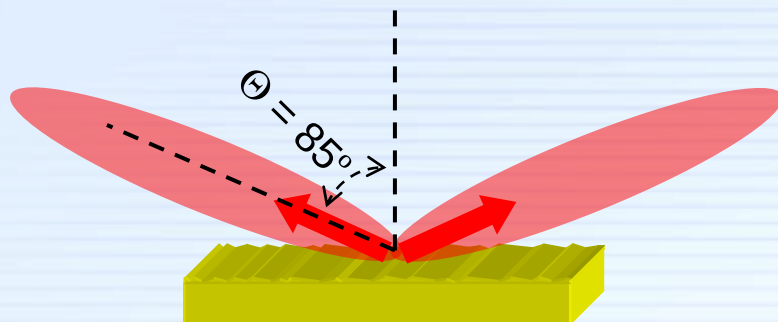
Measured HDR - 8097-2 (Nickel) - $\Lambda=30\ \mu\text{m}$ - 090407





Nearly Planar, High-Angle Emission Component

Emission Simulation of $\Lambda=3\mu\text{m}$ on $\text{Al}/\text{Si}_3\text{N}_4$





Implementation

How do we implement this technology?

The underlying physics gives us a practical, realistic answer.

- The effect is based upon plasmons and their **characteristic propagation length, which is small** (~100 microns).
- The elements can be this size, like **glitter**.
- Dispersed in a liquid, the elements may be **painted** on and will conformally coat an object.

Cylinder emission
without plasmon paint



Cylinder emission
with plasmon paint



Summary

- We are designing, fabricating, and characterizing diffractive structures that couple plasmons to photons for emission management.
- We expect that if a high absorption location is near a plasmon mode and the mode propagates efficiently, the coherent emission will be significant in that wavelength regime.
- We plan to implement this technology as a conformal paint.

