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

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LDRD Day

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LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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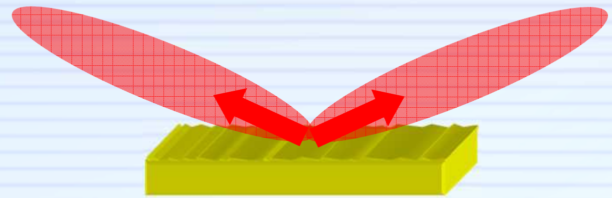
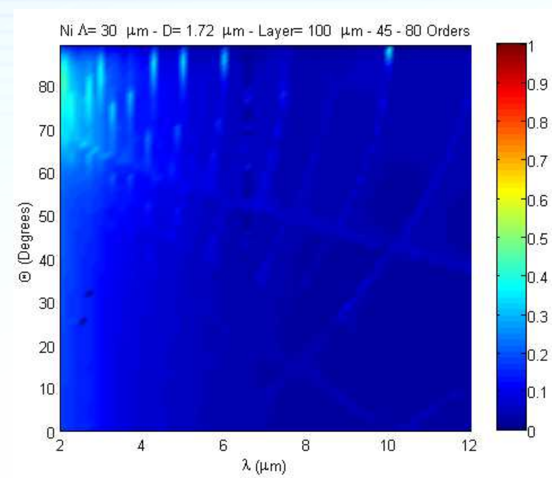
Outline

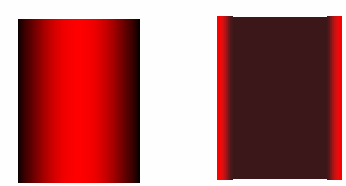


- •Concept
- •Some Applications
- •Hypothesis

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

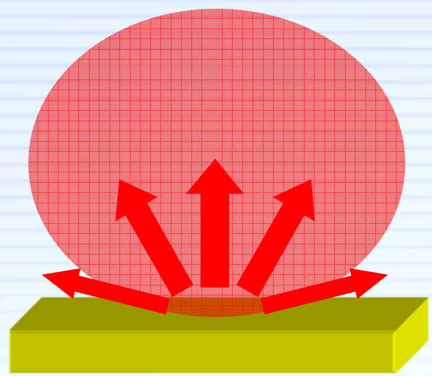
- •Design Process
- •Material Selection
- •Wood's Anomaly
- •Measurements
- •Implementation



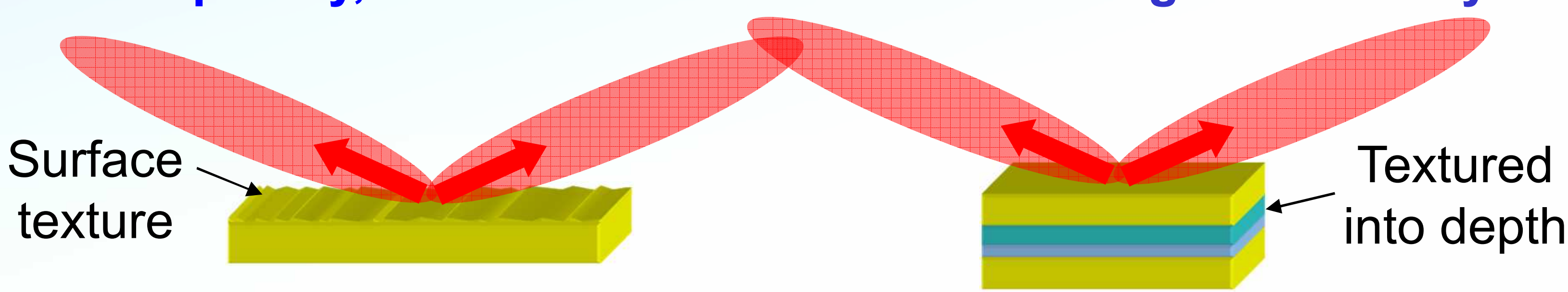


Coherent Thermal Emission Through Photonics/Plasmonics

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

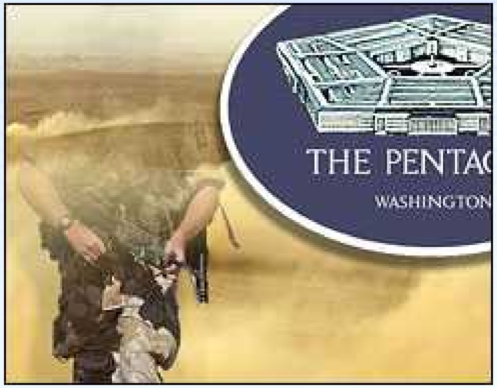
In the News, But Not What We Are Doing

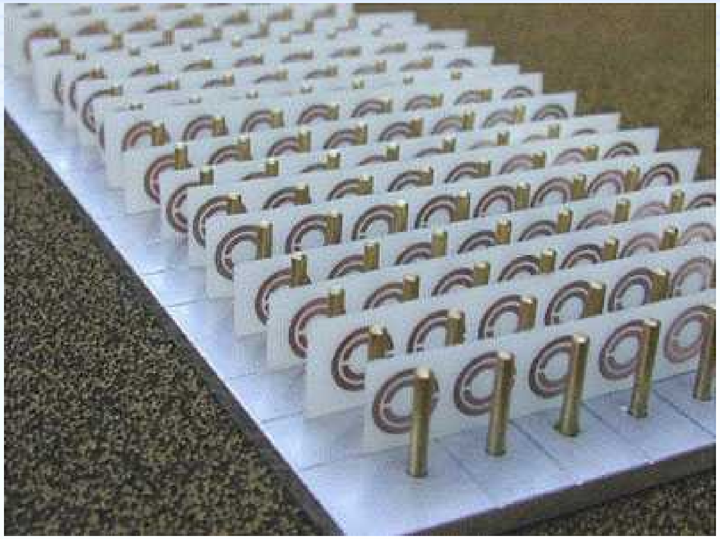
A Real Invisibility Cloak

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**

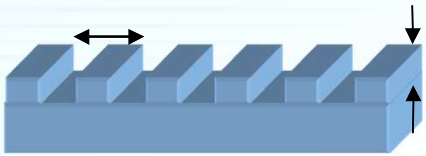
New science:

- **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).

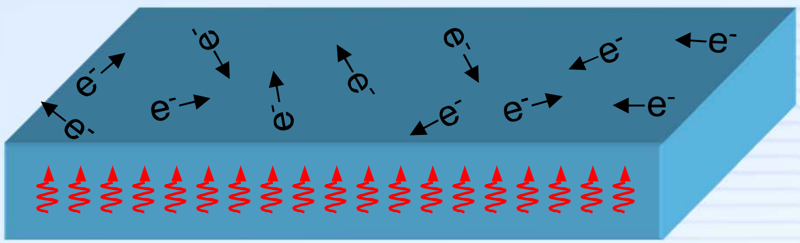
Radiative cooling of semiconductor devices & efficient infrared light sources

•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).

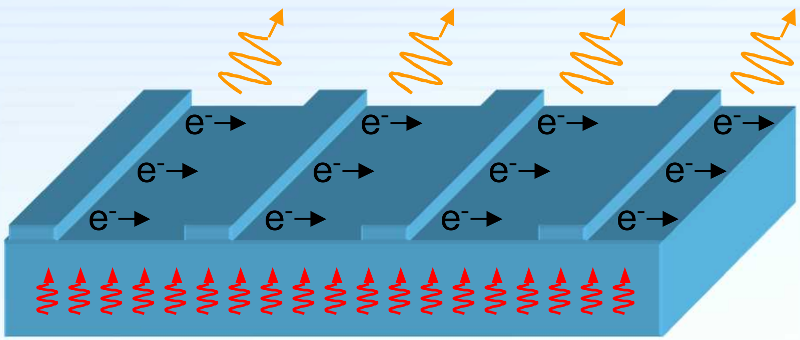
High-efficiency incandescent lamps

•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).

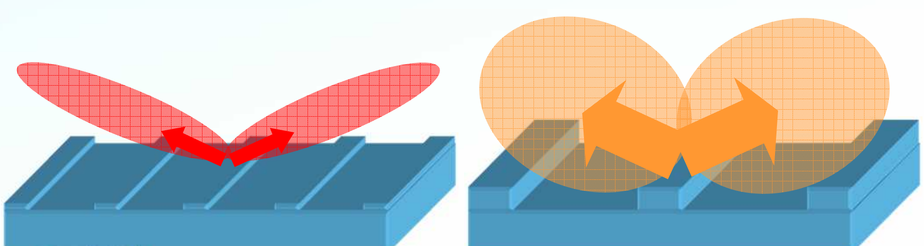
Physical Mechanisms



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 $\varepsilon`_{\lambda}$ 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:

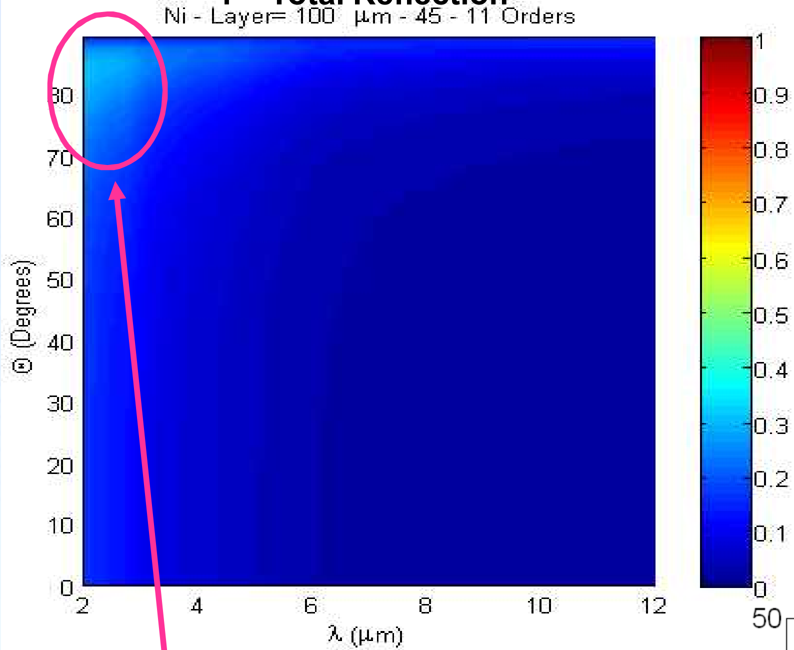
•Material Selection: absorption in a bulk material at large, glancing angles. This happens in materials where $0.5 < n/k < 2$ and their magnitudes do not exceed 10.

•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).

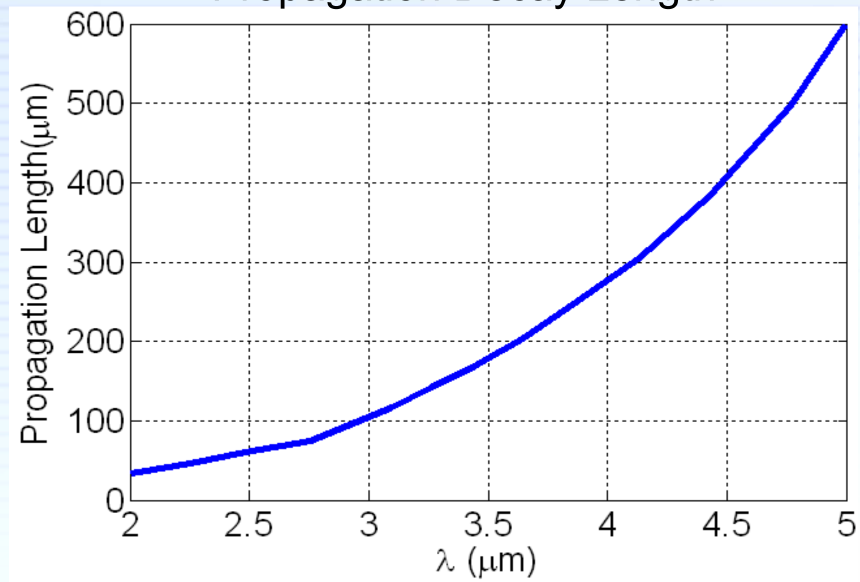
•A Surface-Plasmon Polariton (SPP) appears close to the Wood's Anomaly. It is most effective when its characteristic length is many times the grating period.

Material Selection - Nickel

1 – Total Reflection

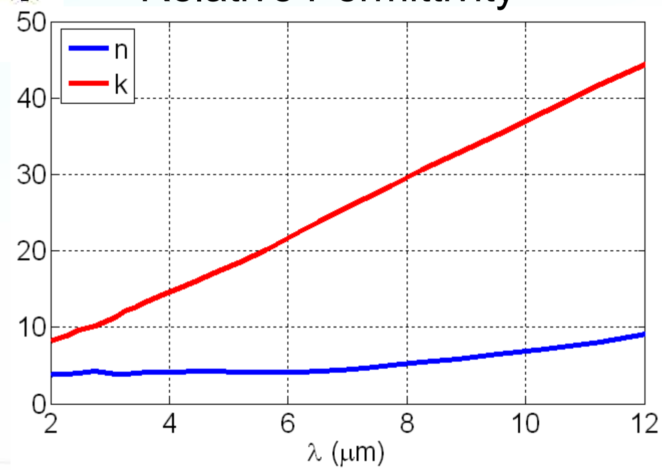


Propagation Decay Length



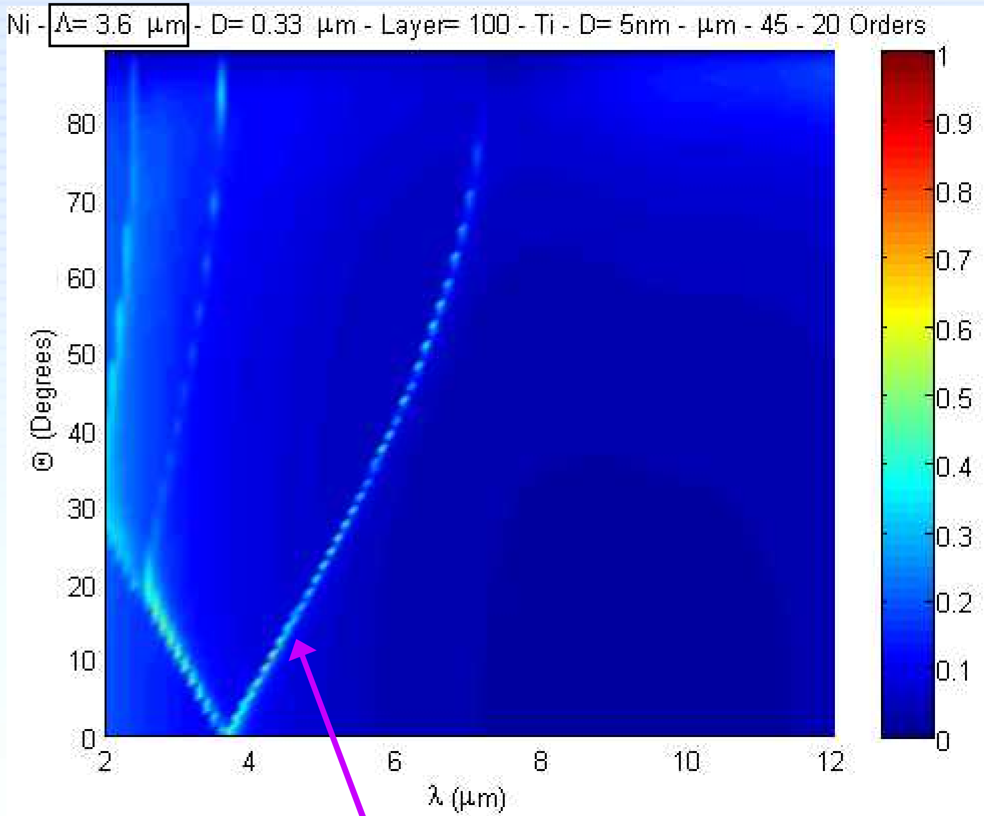
- Long decay length
- Practical sampling with grating period
- High absorption

Relative Permittivity



Wood’s Anomaly - Nickel

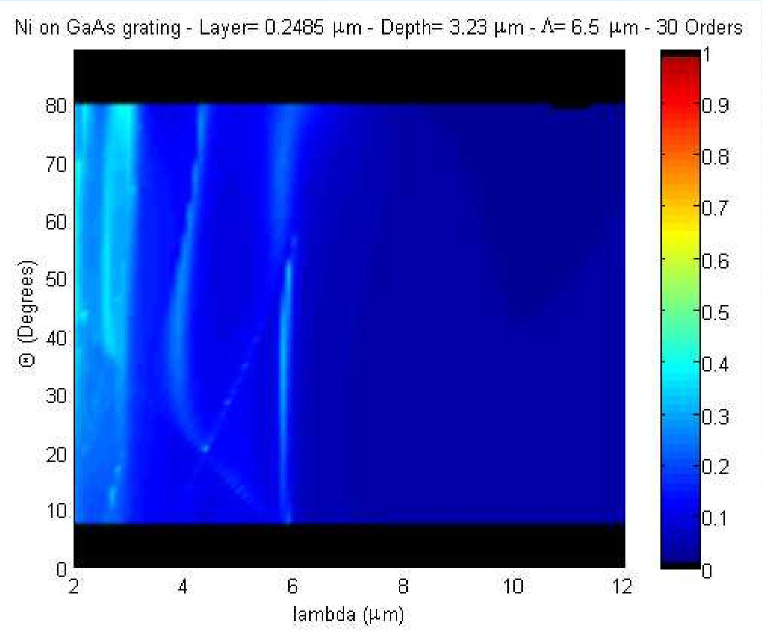
1 – Total Reflection



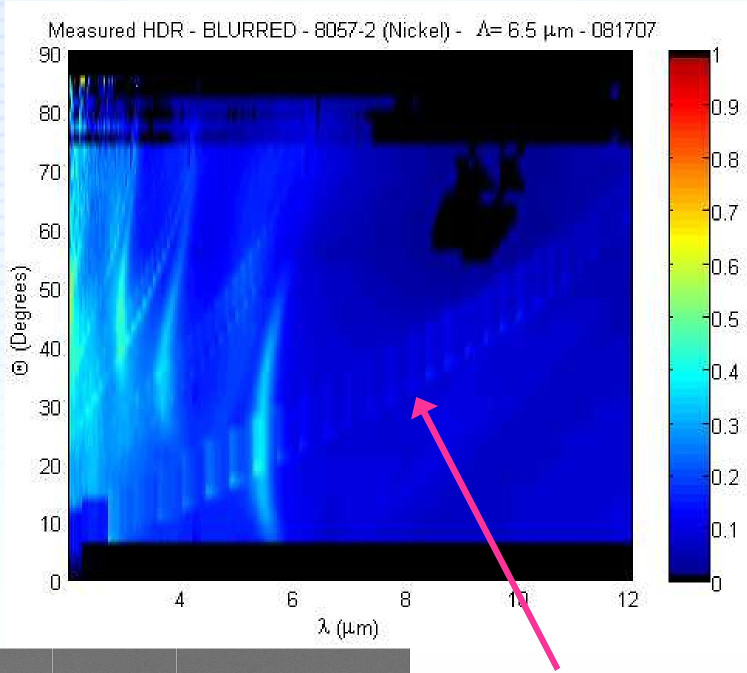
Wood’s Anomaly

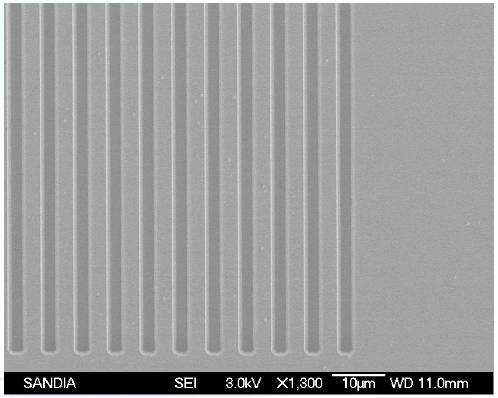
Simulation and Measurement : Nickel with Small Grating Period

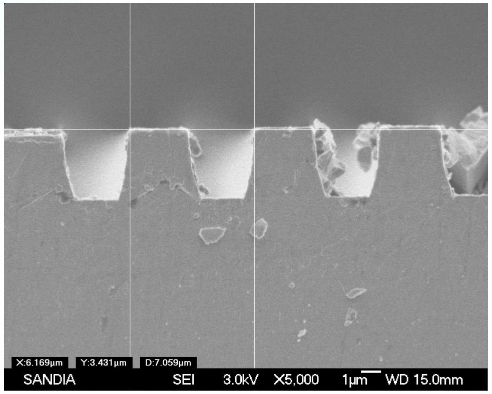
Simulation : 1 – Total Reflection



Measurement =1 – Total Reflection







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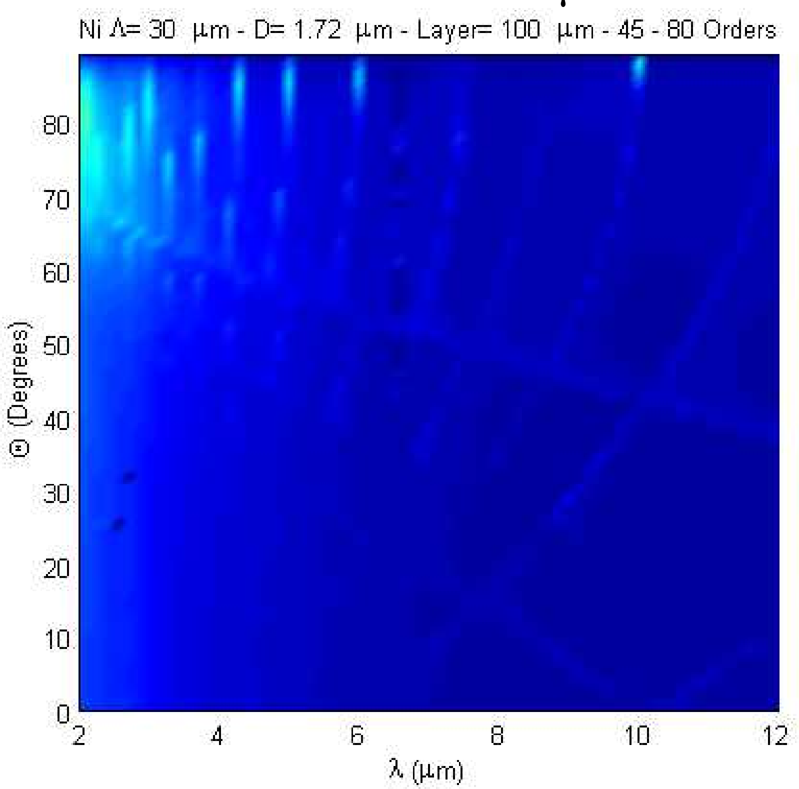
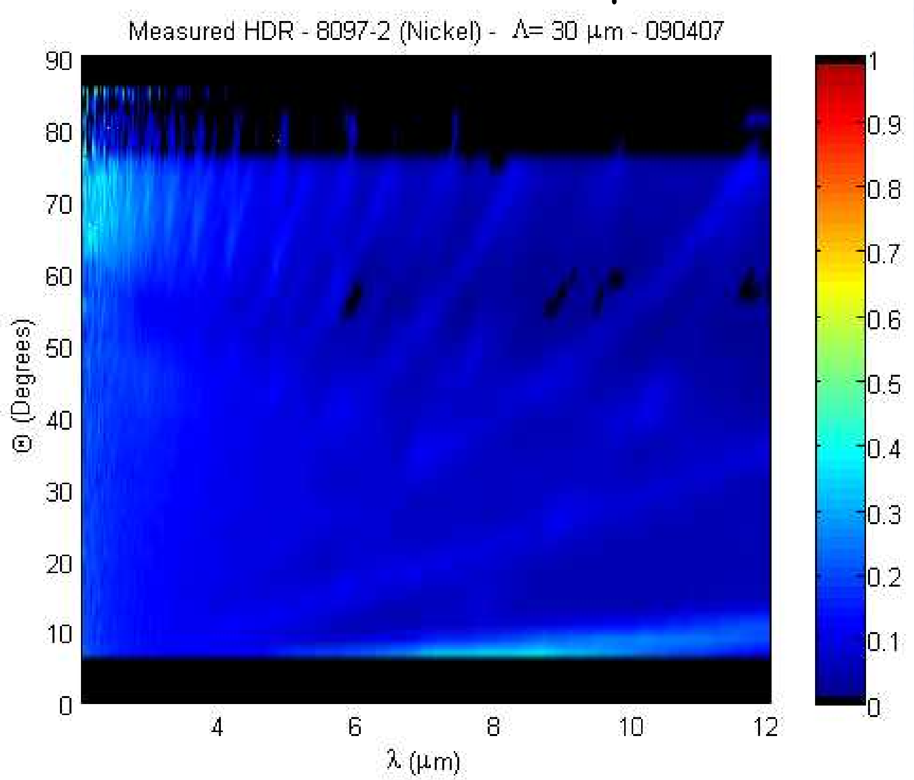
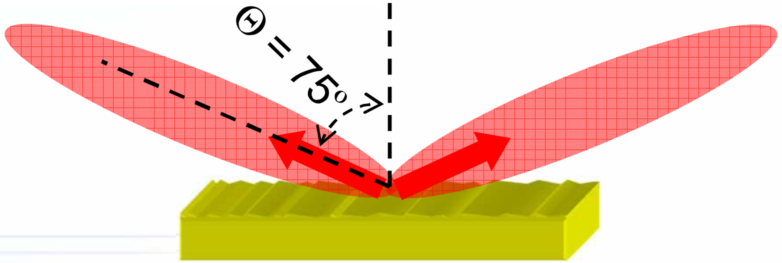
Simulation and Measurement: Nickel with Large Grating Period, High-Angle Emission

Simulation of Λ=30μm on Ni



Measurement of Λ=30μm on Ni





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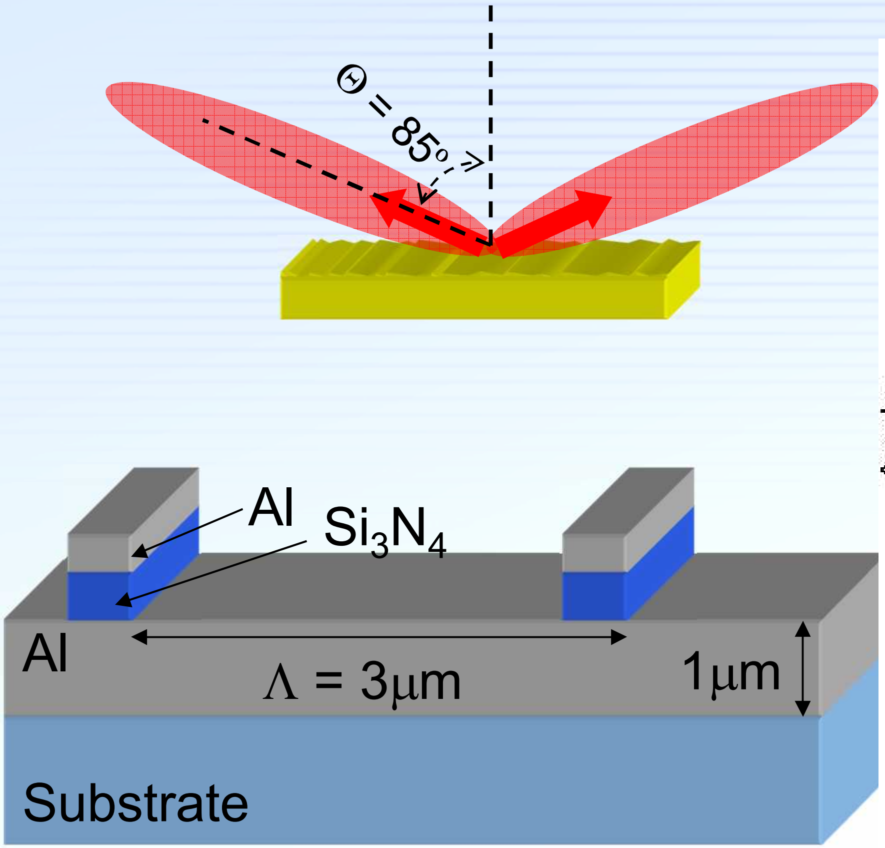
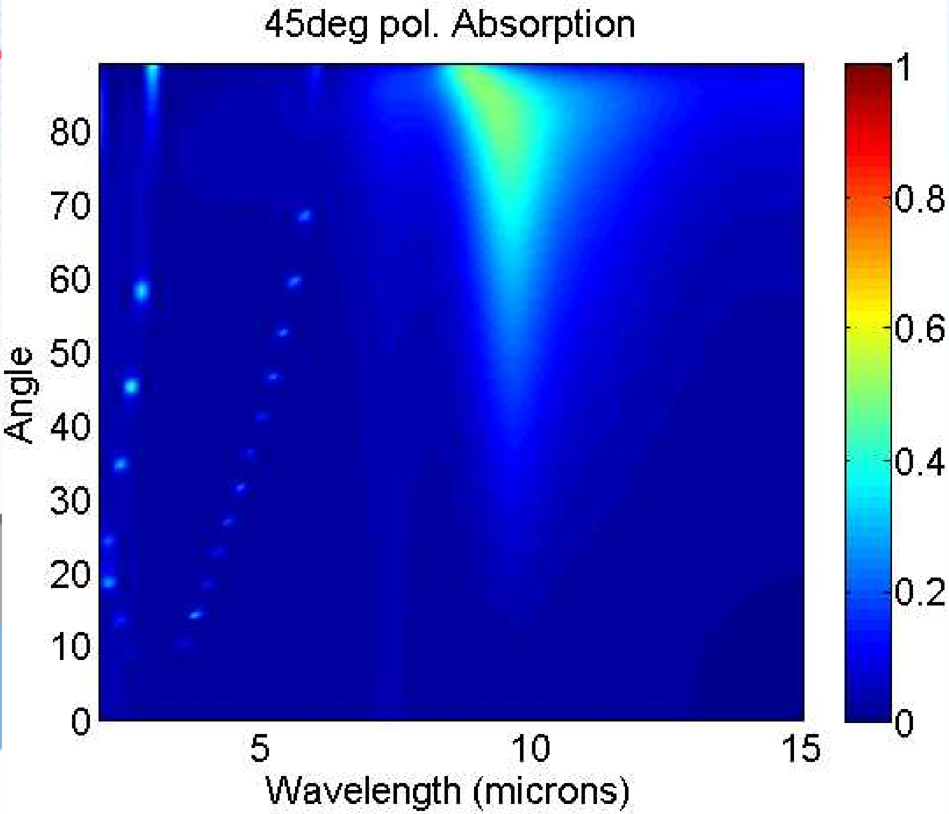
Nearly Planar, High-Angle Emission Component



Emission Simulation of Λ=3μm on Al/Si_3N_4



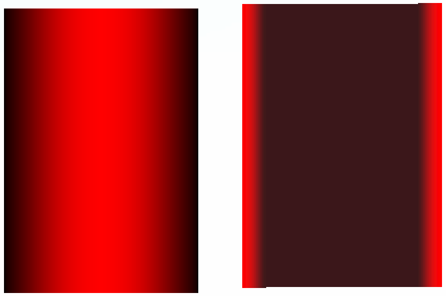
Implementation

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.**

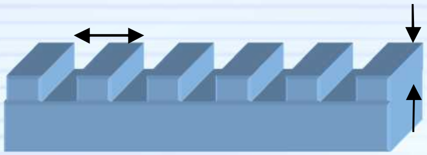
Cylinder emission without plasmon paint



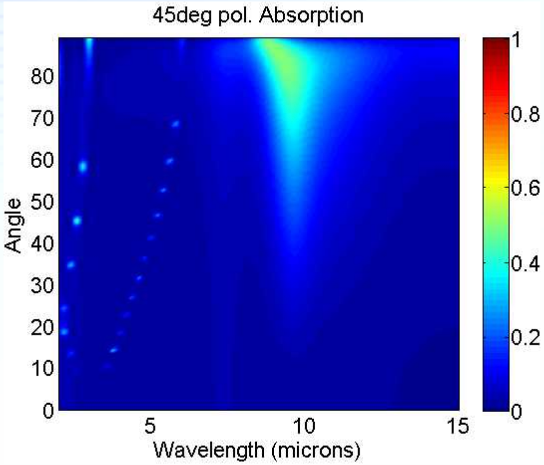
Cylinder emission with plasmon paint

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.