Control of Heat Radiation with Meta materials

ECE 695 – Nanophotonics & Metamaterials
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Outline

• Introduction
• Motivation
• Applications
• Summary
All matter emits thermal radiation due to its finite temperature.

Spectral intensity of emitted radiation:

\[ I_{\lambda,e}(\lambda, \theta, \phi) = \frac{dq (W)}{dA_1 \cos \theta \ d\omega d\lambda} \]

Spectral Emissive power: is the rate at which radiation of wavelength \( \lambda \) is emitted in all directions from a surface per d\( \lambda \) and dA:

\[ E_{\lambda}(\lambda) = \int_{0}^{2\pi} \int_{0}^{\pi/2} I_{\lambda,e}(\lambda, \theta, \phi) \cos \theta \sin \theta d\theta d\phi \]

Total Emissive power:

\[ E = \int_{0}^{\infty} E_{\lambda}(\lambda) d\lambda \]
Black body

• Diffuse emitter: I of emitted radiation is independent of direction

A **blackbody** is one which:
• absorbs all incident radiation over all $\lambda$ and from all directions
• emits the max. possible energy for a given temperature and $\lambda$
• is a diffuse emitter, i.e., radiation is independent of direction

$$E_{\lambda,b}(\lambda, T) = \frac{C_1}{\lambda^5 \left[ \exp \left( \frac{C_2}{\lambda T} \right) - 1 \right]}$$
Spectral Emissive power of black body

Wien’s Displacement Law: \( \lambda_{\text{max}} T = 2897.8 \ \mu\text{m K} \)

Stefan-Boltzmann Law:

\[
E_b = \int_{\lambda}^{\infty} E_{b,\lambda} \, d\lambda
\]

\[
E_b = \sigma T^4
\]

\[
\sigma = 5.67 \times 10^{-8} \ \text{W/m}^2\text{K}^4
\]
Kirchhoff’s Law

Emissivity \equiv \frac{\text{emissive power of surface at some } \lambda, T}{\text{emissive power of b.b. at same } \lambda, T}

\checkmark \text{ based on incident radiation}

Absorptivity : \quad \alpha_{\lambda}(\lambda) = \frac{G_{\lambda, \text{abs}}(\lambda)}{G_{\lambda}(\lambda)}

Kirchhoff’s Law: \quad \varepsilon_{\lambda, \theta} = \alpha_{\lambda, \theta}
Motivation

• Thermal emitting source is often represented as incoherent source, broad spectrum unlike laser
• Controlling the spectral and directionality of thermal radiation can be used in many applications like efficient and cheap IR source, CO₂ detection etc.,
• Engineering the material properties using metamaterials can be used for radiative cooling
Coherent emission of light by thermal sources

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• Periodic microstructure on SiC, thermal Infrared source

• Coherent over large distances (many wavelengths)

• Radiates in well defined directions, narrow angular emission lobes similar to antenna lobes

• Origin of the coherent emission lies in the diffraction of surface-phonon polaritons by the grating
Directional Emissivity

Experimental: The measurements were taken by detecting the intensity emitted by the sample. Theoretical: Using Kirchhoff's law ($\varepsilon = \alpha = 1 - R$)

Angular width of the lobe emission varies qualitatively with $\lambda/l$, where $l$ is coherence length.
Surface Phonon Polaritons

\[ \frac{2\pi}{\lambda} \sin \theta = k_{||} + p \frac{2\pi}{d} \]  
Grating law

where \( p \) is an integer and \( k_{||} \) is the wavevector of the surface wave.

spectral coherence length \( \lambda/\theta \approx 60\lambda \approx 0.6 \text{ mm} \)

Thus, By modifying the characteristics of the surface profile, it is possible to modify the direction.

Emissivity of the source is enhanced by factor of 20.
Directional emissivity for different wavelengths

**Figure 3** Emissivity of a SiC grating in $p$-polarization. Blue, $\lambda = 11.04 \mu m$; red, $\lambda = 11.36 \mu m$; green, $\lambda = 11.86 \mu m$

Experimental: Using Kirchhoff’s law, $R$ from FTIR measurements
Theoretical: Using Kirchhoff’s law \( \epsilon = \alpha = 1 - R \)

**Figure 4** Comparison between measured and calculated spectral reflectivities of a SiC
Spectral Control of Thermal Radiation by Meta surface with Split-Ring Resonator

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Split Ring Resonator (SRR)

- SRRs made of gold are fabricated onto a plane substrate with glass/Cr/Ag/Cr/SiO2 layers
- Silver layer plays role of blocking any thermal radiation from the underlying substrate
- Experimental emission from the FTIR
- To avoid the absorption of water and carbon dioxide, the experimental setup is placed in vacuum
- Numerically emittance is calculated from Kirchhoff’s law
  \[ \varepsilon = \alpha = 1 - \rho \]

The side length and width of the SRR measured after fabrication are \( L_x = L_y = 3.2 \text{ um} \) and \( w = 0.7 \text{ um} \). The period of the structure is 5.0 um.
Relative emittance

Experimental Results

Simulation Results

Electric field Distribution ($E_z$) from the simulations
Changing length of SRR

Experimental Results

Simulation Results
Plasmonic Meta surface for Directional and Frequency-Selective Thermal Emission

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• Meta surface to control simultaneously the spectrum and the directivity of radiation
• 2D periodic array of metal-insulator-metal (MIM) cavities
• Each MIM supports a gap surface plasmon (GSP) mode responsible for the resonant absorption or emission
• The directivity of the emitted radiation is driven by the periodicity of the MIM array
Calculated absorption at normal incidence

The 100% absorption takes place for $L=900$ nm and $h_{SiN} = 120$ nm (black dot)

Period = 3 um fixed, $h$ metal fixed =100 nm
Controlling the direction

(a) Calculated absorptivity as a function of the frequency and the incident K.
The oblique line $\omega = \frac{2\pi c}{p} - cK$ (c being the speed of light, p: periodicity) cuts the horizontal resonance line in two parts, with large absorption on the side of smaller K.

(b) Schematics to explain the reduction of the absorption for large K: (i) for small K values, there is a single diffracted order, whereas (ii) for larger K values, there are two diffracted orders. The existence of the $-1$ order introduces an additional radiative decay channel. When K becomes larger, the diffracted order $-1$ becomes propagating, and the absorption becomes $1 - R(0) - R(-1)$.

(c) Calculated absorptivity at $\lambda = 4.25 \, \mu m$ as a function of the normalized $k_x$ and $k_y$.

More precisely, the position of this first-order cutoff is given by $\sin^{-1}(\lambda - p)/p$. Here, with $p = 3 \, \mu m$ and $\lambda = 4.25 \, \mu m$, we find $\theta = 24.6^\circ$. 
Experimental Measurements

(a) SEM image of the MIM grating showing the size of the square side and of the period

(b) Measured reflectivity R0 normalized by a gold surface, plotted as the map of 1 − R0. The experimental measurement spans from 13 to 90

(c) Enlarged anticrossing zone in the measured 1 − R0 map in p polarization for samples with L = 900 nm and different periods, (i) p = 2.7 μm, (ii) p = 3 μm

By decreasing the period, the anticrossing point shifts towards higher K (vertical dashed line)
Passive radiative cooling below ambient air temperature under direct sunlight

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• Experimentally demonstrate radiative cooling to nearly 5 degrees Celsius below the ambient air temperature under direct sunlight

• Engineer the material properties using meta materials such that absorptivity is minimal in solar spectrum region and emissivity is high in the atmospheric transparency window
• The net cooling power $P_{cool}$ of a radiative cooler is given by

$$P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{sun} - P_{cond+conv}$$

On 200-mm-diameter Si wafer substrate

Emissivity/absorptivity of the photonic radiative cooler from the ultraviolet to the mid-infrared
Temperature of photonic radiative cooler
Cooling Power

• Thermal Radiation can be controlled spectrally and directionally using Meta materials.
  a) Grating
  b) Split Ring Resonators
  c) 2D periodic array of metal-insulator-metal (MIM) cavities

• Passive Radiative cooling by engineering the material properties by using the meta materials
Questions?

Thank you