Control of Heat Radiation with Meta materials

ECE 695 – Nanophotonics & Metamaterials
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Prabhu Kumar Venuthurumilli
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 \( dA \):

\[ E_{\lambda}(\lambda) = \int_0^{\pi/2} \int_0^{2\pi} I_{\lambda,e}(\lambda, \theta, \phi) \cos \theta \, \sin \theta \, d\theta \, d\phi \]

Total Emissive power

\[ E = \int_0^{\infty} E_{\lambda}(\lambda) \, d\lambda \]
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

$$E_{\lambda, b}(\lambda, T) = \frac{C_1}{\lambda^5 \exp \left( \frac{C_2}{\lambda T} \right) - 1}$$
Wien’s Displacement Law: \( \lambda_{\text{max}} T = 2897.8 \ \mu\text{m} \ K \)

Stefan-Boltzmann Law:
\[
E_b = \int_0^\infty E_{b,\lambda} \, d\lambda
\]
\[
E_b = \sigma T^4
\]
\[
\sigma = 5.67 \times 10^{-8} \ \text{W/m}^2\text{K}^4
\]
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} \quad \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}
• 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

Jean-Jacques Greffet*, ReÂmi Carminati*, Karl Joulain*, Jean-Philippe Mulet*, SteÂphane Mainguy² & Yong Chen³

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* Laboratoire EM2C, CNRS, Grande Voie des Vignes, ChaÃtenay-Malabry 92295 Cedex, France
² CEA CESTA, Le Barp, 33114, France
³ Laboratoire de Microstructures et de MicroeÂlectronique, CNRS, av. H. Ravera, 92220 Bagneux, France
• 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

![Image of a grating obtained by atomic force microscopy. Its period $d = 0.55\lambda$ ($\lambda = 11.36 \mu m$) was chosen so that a surface wave propagating along the interface could be coupled to a propagating wave in the range of frequencies of interest. The depth $h = \lambda/40$ was optimized so that the peak emissivity is 1 at $\lambda = 11.36 \mu m$. It was fabricated on SiC by standard optical lithography and reactive ion-etching techniques.](image)

Heated to 773 K

Experimental: The measurements were taken by detecting the intensity emitted by the sample

Theoretical: Using Kirchhoff's law $\epsilon = \alpha = 1 - R$

Angular width of the lobe emission varies qualitatively with lambda/l, where l is coherence length

Red, experimental data; Green, theoretical calculation
Surface Phonon Polaritons

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

Grating law

where \( p \) is an integer and \( k_\parallel \) is the wavevector of the surface wave

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

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 $\rho$-polarization. Blue, $\lambda = 11.04\,\mu\text{m}$; red, $\lambda = 11.36\,\mu\text{m}$; green, $\lambda = 11.86\,\mu\text{m}$

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

Yosuke Ueba and Junichi Takahara
Osaka University, Japan

Applied Physics Express 5 (2012) 122001
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 $\varepsilon = \alpha = 1 - R$.

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.

Fig. 1. Microscope image of SRRs fabricated on the silver-inserted substrate. Inset: enlarged image of the sample (left) and conceptual design of SRR array for thermal radiation control.
Relative emittance

Experimental Results

Simulation Results

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

Experimental Results

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

D. Costantini, A. Lefebvre, A.-L. Coutrot, I. Moldovan-Doyen, J.-P. Hugonin, S. Boutami, F. Marquier, H. Benisty, and J.-J. Greffet

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1Laboratoire Charles Fabry, Institut d’Optique, CNRS, Université Paris-Sud, 2 avenue Augustin Fresnel, 91127 Palaiseau cedex, France
2Université Grenoble Alpes F-38000 Grenoble, France CEA, LETI, MINATEC Campus, F-38054 Grenoble, France
• 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 $h_{\text{SiN}} = 120$ nm (black dot).

Period = 3 um fixed, h metal fixed = 100 nm
(a) Calculated absorptivity as a function of the frequency and the incident K.
The oblique line $\omega = 2\pi c/p - cK$ (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 $1 - R_0$. The experimental measurement spans from $13^\circ$ to $90^\circ$

(c) Enlarged anticrossing zone in the measured $1 - R_0$ map in p polarization for samples with $L = 900$ nm and different periods, (i) $p = 2.7 \, \mu m$, (ii) $p = 3 \, \mu m$

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

Aaswath P. Raman\textsuperscript{1}, Marc Abou Anoma\textsuperscript{2}, Linxiao Zhu\textsuperscript{3}, Eden Rephaeli\textsuperscript{1} & Shanhui Fan\textsuperscript{1}

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\textsuperscript{1}Ginzton Laboratory, Department of Electrical Engineering, Stanford University, Stanford, California 94305, USA.

\textsuperscript{2}Department of Mechanical Engineering, Stanford University, Stanford, California

\textsuperscript{3}Department of Applied Physics, Stanford University, Stanford, California 94305, USA.
What is this paper about?

• 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
Engineering the emissivity

- The net cooling power $P_{\text{cool}}$ of a radiative cooler is given by

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

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

[Diagram showing the components of a photonic radiative cooler]

[Graphs showing temperature changes over time and solar irradiance]
Summary

• 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