Tailoring Light Emission with Metasurfaces

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This work has been supported by the Agence Nationale de la Recherche, NanoK, Labex NanoSaclay, Institut Universitaire de France, SAFRAN-IOGS chair on Ultimate Photonics.
Outline

1. Tailoring incandescence with resonant metasurfaces
2. Tailoring photoluminescence with resonant metasurfaces
Application of MIR sources

- Gas detection
- IR spectroscopy
- Communications

Globar

OPO

• QCL
Incandescent metasurfaces for IR radiation

1. Isotropic,
2. Wide spectrum,
3. Slow modulation rate,
4. Low efficiency,
5. Low brightness.

Black body: Planck’s law \( L_0(T, \lambda) \)
1. Spatial coherence

- Directional thermal source

Greffet et al., *Nature* 2002
1. Spatial coherence

Origin of the spatial coherence

Coherence is due to the field of the surface phonon polariton mode (any extended mode can be used).
Coupling is due to the grating.
2. Temporal coherence

Thermal source with narrow spectrum

Liu et al., *PRL* 2011

Puscasu et al., APL 92, 233102 (2008)
A key tool: Kirchhoff law

\[ d\Phi = I_\lambda \ dS \ \cos \theta \, d\Omega \]

\[ I_\lambda = \varepsilon_\lambda(\theta) \ I_\lambda^o(T) \]

\[ \varepsilon_\lambda = \alpha_\lambda = 1 - R_\lambda \]

Opaque body

Thermodynamics
Radiometry world

Electrodynamics
Coherent optics world
3. Fast modulation of the emission

\[ d\Phi = I_\lambda \ dS \ \cos \theta d\Omega \]

\[ I_\lambda = \epsilon_\lambda(\theta) \ I_\lambda^o(T) \]

Design strategy:

- Modulation of temperature
- Modulation of emissivity

3. Fast modulation of the emission

Kim et al., Nano Lett. 2018, 18, 934

Miyoshi et al., Nat. Commun. doi: 10.1038/s41467-018-03695-x
Modelling thermal emission

A **Langevin type** model to compute emitted fields by statistical ensembles of sources in local thermodynamic equilibrium.

\[ E_m(r, \omega) = i\mu_0 \omega \int G_{mn}(r, r', \omega) j_n(r', \omega) d^3r', \]

\[ W_{jn,jn}(r, r', \omega) = 2\omega \varepsilon_0 \text{Im}[\varepsilon_{ib}(r', \omega)] \Theta(T, \omega) \delta(r-r') \delta_{nn}, \]

Emission

Absorption
Local Kirchhoff law

Generalization to anisothermal bodies

\[ dP_e^{(l)} = d\Omega \int_0^\infty d\omega \int_V d^3r' \alpha^{(l)}(-u, r', \omega) \times \frac{\omega^2}{8\pi^3 c^2} \frac{\hbar \omega}{\exp(\frac{\hbar \omega}{k_B T}) - 1}, \]

\[ \sigma_{\text{abs}}^{(l)}(u_{\text{inc}}, \omega) = \int_V d^3r' \alpha^{(l)}(u_{\text{inc}}, r', \omega), \]

Emission

Absorption

Incandescent metasurface

Constraints:

Cooling time
High temperatures
Emissivity
Electrical impedance
Pulse emission

![Graph showing pulse emission with a peak width of 6.7 μs]
Frequency response

![Graph showing frequency response with regimes labeled as regime 1, regime 2, and regime 3. The x-axis represents modulation frequency ($f_{th}$ in Hz), and the y-axis represents emitted signal (a.u.). Two types of polarization are shown: TE and TM.]
Emission spectrum

Radiance: $6 \times 10^{-7}$ W sr$^{-1}$

Wall-plug efficiency: $10^{-6}$ at 20 kHz
Outline

1. Tailoring incandescence with resonant metasurfaces
2. Tailoring photoluminescence with resonant metasurfaces
Key features of an emitting metasurface

Controlling light emission

- Direction
- Spectrum
- Polarization
- Efficiency (light extraction)
Tailoring light emission by single emitters with nanoantennas

Light emission by an ensemble of thermalized emitters in a resonant system

Cavity

Metallic Metasurface

Dielectric Metasurface

Klaers et al., Nature 468, 545 (2010)

S. Rodriguez et al., PRL 111, 166802 (2013)

T. Bucher et al., ACS Photon 6, 1002 (2019)
## Light emission in a resonant system

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- **Vacuum**
  - Single emitter
  - Two-levels system
  - Einstein coefficient

- **Cavity**
  - CQED, Purcell effect
  - ?
Light emission in a resonant system

Light emission by an ensemble of PbS QDs:

Quenching on a gold film
No quenchanting on a gold metasurface

Le-Van et al., Nature Communications 7, 12017 (2016)
Light emission in a resonant system

Light emission by an ensemble of PbS QDs:

spectral modifications

Modelling light emission by a thermalized ensemble of electrons/molecules
Light emission by a thermalized ensemble of electrons/molecules

Rovibrational band of excited electronic states in a molecule or conduction band in a semiconductor or Inhomogeneous distribution of QDs.

Thermalization is faster than light emission.
Light emission by a thermalized ensemble of electrons/molecules (1)

Light emission by an ensemble of emitters in a resonant system (2)

A Langevin type model to compute emitted fields by statistical ensembles of sources in local thermodynamic equilibrium.

\[ E_m(r, \omega) = i\mu_0\omega \int G_{mn}(r, r', \omega) j_n(r', \omega) d^3r', \]

It can be used for electroluminescence and photoluminescence.
Modelling light emission by an ensemble of thermalized emitters in a resonant system

Fluorescence/Electroluminescence:

\[ E_m(r, \omega) = i\mu_0\omega \int G_{mn}(r, r', \omega) j_n(r', \omega) d^3r', \]

\[ W_{jn,jm}(r, r', \omega) = 2\omega e_0 \text{Im}(\epsilon_{bi}(r', \omega, \mu)) \Theta[T, \omega, \mu] \delta(r-r') \delta_{nm}, \]

\[ \Theta[T(r'), \omega, \mu(r')] = \frac{\hbar \omega}{\exp(\frac{\hbar \omega}{k_B T} - 1).} \]

The photon chemical potential accounts for the applied voltage or the optical pumping. (Wurfel, J.Phys.C 15, 3967 (1982)). Only the interband transition contribution to \( \text{Im}(\varepsilon) \) is Included.

Light emission by an ensemble of emitters in a resonant system

The model accounts for the interplay between gain/losses and cavity.

\[ E_m(r, \omega) = i \mu_0 \omega \int G_{mn}(r, r', \omega) j_n(r', \omega) d^3 r', \]

Local Kirchhoff law

\[ dP_e^{(l)} = d\Omega \int_0^\infty d\omega \int_V d^3r' \alpha^{(l)}(-u, r', \omega) \times \frac{\omega^2}{8\pi^3 c^2} \frac{\hbar \omega}{\exp(\frac{\hbar \omega - \mu}{k_B T}) - 1} \]

Physics of the excitation: \( T \) and \( \mu \)

\[ \sigma_{abs}(u_{inc}, \omega) = \int_V d^3r' \alpha^{(l)}(u_{inc}, r', \omega), \]

Checking thermalization for photoluminescence

Wien’s approximation of the Bose Einstein factor

\[ I_{pl}(E) \propto \varepsilon(E) \exp \left( -\frac{E}{kT_{eh}} \right). \]

Plotting \( \ln(I) \) vs \( h\nu \) gives the temperature.

Photoluminescence by thermalized systems

Emission by InAlAs/InGaAs quantum wells

\[ I_{pl}(E) \propto \varepsilon(E) \exp \left( -\frac{E}{kT_{eh}} \right). \]

Pump at 532 nm, 200 fs

S. Rodriguez et al., PRL 111, 166802 (2013)

CW pump at 1064 nm

L. Hirst et al., IEEE J. PV 4, 1526 (2014)
Modeling photoluminescence
Electroluminescence by thermalized systems

Spectral changes

Electroluminescence by thermalized systems

Absence of quenching

Summary

Single emitter
- Two-levels system
- Einstein coefficient

Thermalized emitters
- LED
- Kirchhoff law

Cavity
- CQED, Purcell effect

Vacuum
- Local Kirchhoff law
Summary and outlook

Kirchhoff law accounts for the interplay between thermalisation, gain and cavity effects.

Quenching, spectral modifications, ASE cannot be explained by incoherent addition of

To be explored: time dynamics emission, control of polarization, efficiency optimization, photon condensation.