Optical Resonator Modulated Super-Plankian Monochromatic Thermal Radiation in Near-field

Baoan Liu and Sheng Shen[*]

Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[*]corresponding author: sshen1@cmu.edu

Abstract-We propose a general methodology to achieve the super-Planckian monochromatic thermal radiation by designing the emitter-absorber optical resonator. The monochromatism can thus be controlled by the resonance mode, rather than the material intrinsic properties. A general theory based on the quasinormal modes of the resonator is derived to qualitatively guide the design of the emitter-absorber resonator.

Thermal radiation, which was regarded as broadband and less-intensive because of Planck's law, can simultaneously be monochromatic and super-Planckian in near-field[1]. The super-Planckian monochromatic thermal emission shows great potentials in the fields of renewable energy[2], information interconnects[3], and infrared super-resolution sensing[4]. However, so far the only solution to realizing the super-Planckian monochromatic near-field thermal radiation is to utilize the intrinsic resonance of the polar dielectric thermal emitters/absorbers (e.g. SiC, SiO_2), where the peak frequency corresponds to the resonance of surface phonon polariton, i.e. $\varepsilon \approx -1$[1]. In this scenario, the monochromatism is determined by the material property, which severely limits the engineering applications.

In this presentation, we propose a general methodology to achieve the super-Planckian monochromatic thermal radiation by designing the emitter-absorber optical resonator. The thermal radiative energy flux peaks correspond to the frequencies of the cavity resonance modes. Therefore, the monochromatism can be designed by the geometrical structures, rather than the material intrinsic properties. In general, the emitter and absorber can be made by non-resonance materials (e.g. metals, graphene, etc.).

First, we present a general theory to quantitatively predict and interpret the peaks in the energy flux spectrum based on the quasinormal modes (QNM)[5] of the emitter-absorber resonator. We demonstrate that the peaks follow the Lorentz line-shape whose apex value can be estimated by a simple equation as

$$\phi(\omega_n) \approx \frac{2}{\pi}\left[\Theta(\omega_n, T_E) - \Theta(\omega_n, T_A)\right]\eta_a \eta_e \tag{1}$$

where $\Theta(\omega,T) = \hbar\omega / \left(\exp[\hbar\omega / k_B T] - 1\right)$ is the Planck's distribution; $\eta_a = Q_a / \left(Q_a + Q_e + Q_f\right)$ and $\eta_e = Q_e / \left(Q_a + Q_e + Q_f\right)$ are the fractional energy loss of the QNM in the absorber and emitter, respectively. Here, Q_a and Q_e indicate the resistive dissipation of the QNM inside the absorber and emitter, respectively. Q_f is the far-field radiation loss of the QNM. This theory serves as a general design principle for the optical resonator modulated near-field thermal radiation. To maximize the monochromatic thermal radiative energy transfer, the resonance mode of the emitter-absorber resonator needs to be designed such that $\eta_a = \eta_e = 0.5$, i.e. the mode loss inside the emitter and the absorber are equally distributed, and the fractional far-field radiation loss is negligible.

After that, we demonstrate that the thin metal wire and graphene serve as two possible building blocks of the optical resonator thermal emitter/absorber with ideal performance. We also confirm our theory by comparing with the direct simulation results by the Fluctuating Surface Current method[6].

Acknowledgements, the authors acknowledge funding support from National Science Foundation (CBET-1253692).

REFERENCES

1. Joulain, K., Mulet, J.-P., Marquier, F., Carminati, R. & Greffet, J.-J. "Surface electromagnetic waves thermally excited: Radiative heat transfer, coherence properties and Casimir forces revisited in the near field," Surf. Sci. Rep. 57, 59–112 2005.
2. Basu, S., Zhang, Z. M. & Fu, C. J. "Review of near-field thermal radiation and its application to energy conversion," Int. J. Energy Res. 33, 1203–1232 2009.
3. Liu, B., Liu, Y. & Shen, S. "Thermal plasmonic interconnects in graphene," Phys. Rev. B 90, 195411 2014.
4. De Wilde, Y. et al. "Thermal radiation scanning tunnelling microscopy," Nature 444, 740–3 2006.
5. Sauvan, C., Hugonin, J. P., Maksymov, I. S. & Lalanne, P. "Theory of the Spontaneous Optical Emission of Nanosize Photonic and Plasmon Resonators," Phys. Rev. Lett. 110, 237401 2013.
6. Rodriguez, A. W., Reid, M. T. H. & Johnson, S. G. "Fluctuating-surface-current formulation of radiative heat transfer: Theory and applications," Phys. Rev. B 88, 054305 2013.