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Abstract

Near-field effect can greatly enhance the radiative heat transfer, by taking advantage of surface resonances. In this paper, we present a numerical approach to use coupled-mode theory for the analysis of near-field radiation. We show that by matching the resonant modes on two objects, the near-field radiation can be maximized. The principle can be applied to the designing of different thermal radiation devices, such as thermophotovoltaic (TPV), thermoradiative (TR), and negative electroluminescent (EL) cooling devices.

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Coupled-Mode Analysis for Near-Field Thermal Radiation Devices

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***Abstract*—Near-field effect can greatly enhance the radiative heat transfer, by taking advantage of surface resonances. In this paper, we present a numerical approach to use coupled-mode theory for the analysis of near-field radiation. We show that by matching the resonant modes on two objects, the near-field radiation can be maximized. The principle can be applied to the designing of different thermal radiation devices, such as thermophotovoltaic (TPV), thermoradiative (TR), and negative electroluminescent (EL) cooling devices.**

***Index Terms*—Thermal radiation, near-field, nanophotonics.**

Near-field radiation is an important heat transfer mechanism that has great potential in many applications, including thermal imaging, sensing, energy conversion in thermophotovoltaic (TPV) and thermoradiative (TR) systems, and cooling applications with negative electroluminescent (EL) cooling devices [1]. The radiative energy transfer between two objects are the enabling physical mechanism for all devices list above. Therefore it is desirable to calculate the radiative transfer precisely and find ways to maximize it. In the following we illustrate our development of numerical calculations based on coupled-mode analysis with a TPV system.

A TPV system converts heat into electricity through thermal radiation [2], and consists of a thermal emitter and a semiconductor photovoltaic (PV) cell. A heat source keeps the thermal emitter at a high temperature, and generates thermal radiation, which is then absorbed by the PV cell with bandgap energy $E_g = \hbar\omega_g$ [3]. Photons with energy lower than E_g cannot generate conducting electrons and are unusable; photons with energy much higher than E_g can generate electron-hole pairs, but the additional energy higher than E_g contributes to thermal loss and is wasted. However, for a far-field based system the emission power is limited by the blackbody radiation, and the emissivity cannot exceed unity at any given frequency. Therefore, the emission power from the emitter would be infinitesimally small assuming a monochromatic radiation spectrum. On the other hand, the near-field based radiative heat transfer can exceed the blackbody limit due to the contributions from evanescent modes [4], especially when resonant modes are supported by the emitter and/or absorber. The analysis of resonant modes is critical for near-field radiation based system.
TPV system [6]. Optimal designs with impedance matching

Conventionally, radiative heat transfer between an emitter and an absorber is quantified using dyadic Green function and the fluctuation-dissipation theorem [4]. The approach is rigorous, but the resulting expressions are complicated and not straighforward to analyze. Recently, coupled-mode theory (CMT) has been developed for emitters supporting resonant modes [5], and radiative heat transfer in a near-field principal for different material systems have also been investigated [7]. So far the CMT is limited to the mode analysis of the TPV system. The important performance parameters of the system, including emissivity, radiation power and output electric power are still calculated with dyadic Green function and the fluctuation-dissipation theorem. And the proposed systems are limited to planar layered configurations. For periodically structured surfaces, effective medium approach is typically used to approximate the structures as a medium with flat surface with effective material properties. It was shown recently that this method fails to predict the near-field radiative transfer behavior due to certain geometry-induced resonant modes.

In this paper, we represent the calculation of all performance parameters of a near-field thermal radiation device including transmissivity, radiation power, and the electric power. For a near-field TPV device, the efficiency based on resonant modes supported by the system can also be calculated accordingly. Furthermore, we expand the calculation to systems with periodic nanostructures supporting additional resonant modes. We show that these modes are captured using coupled-mode method, and can bring the resonant peak closer to the bandgap energy E_g of a typical TPV cell, therefore increasing the radiative heat transfer rate, and the output electric power.

REFERENCES

[1] S. Basu, Z. M. Zhang, and C. J. Fu, "Review of near-field thermal radiation and its application to energy conversion," *International Journal of Energy Research*, vol. 33, no. 13, pp. 1203–1232, 2009. [Online]. Available: http://dx.doi.org/10.1002/er.1607

[2] P. Würfel and U. Würfel, *Physics of Solar Cells: From Basic Principles to Advanced Concepts*, ser. Physics textbook. Wiley, 2009. [Online]. Available: https://books.google.com/books?id=w6Ii4r7FuskC

[3] C. Ferrari, F. Melino, M. Pinelli, P. Spina, and M. Venturini, "Overview and status of thermophotovoltaic systems," *Energy Procedia*, vol. 45, pp. 160 – 169, 2014, {ATI} 2013 - 68th Conference of the Italian Thermal Machines Engineering Association. [Online]. Available: //www.sciencedirect.com/science/article/pii/S1876610214000198

[4] D. Polder and M. Van Hove, "Theory of radiative heat transfer between closely spaced bodies," *Phys. Rev. B*, vol. 4, pp. 3303–3314, Nov 1971. [Online]. Available: http://link.aps.org/doi/10.1103/PhysRevB.4.3303

[5] L. Zhu, S. Sandhu, C. Otey, S. Fan, M. B. Sinclair, and T. Shan Luk, "Temporal coupled mode theory for thermal emission from a single thermal emitter supporting either a single mode or an orthogonal set of modes," *Applied Physics Letters*, vol. 102, no. 10, 2013. [Online]. Available: http://scitation.aip.org/content/aip/journal/apl/102/10/10.1063/1.4794981

[6] A. Karalis and J. D. Joannopoulos, "Temporal coupled-mode theory model for resonant near-field thermophotovoltaics," *Applied Physics Letters*, vol. 107, no. 14, 2015. [Online]. Available: http://scitation.aip.org/content/aip/journal/apl/107/14/10.1063/1.4932520

[7] C. Lin, B. Wang, K. H. Teo, and P. Bandaru, "Application of impedance matching for optimal emitter/absorber design in a thermophotovoltaic system," *Phys. Rev. Appl.*, vol. 7, p. 034003, 2016.