Radiative heat transfer assisted by carbon nanotubes

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Abstract

Near-field heat transfer between two closely spaced radiating media can exceed in orders radiation through the interface of a single black body. This effect is caused by exponentially decaying (evanescent) waves which form the photon tunnel between two transparent boundaries. However, in the mid-infrared range it holds when the gap between two media is as small as few tens of nanometers. We propose a new paradigm of the radiation heat transfer which makes possible the strong photon tunneling for micron thick gaps. For it the air gap between two media should be modified, so that evanescent waves are transformed inside it into propagating ones. This modification is achievable using a metamaterial so that the direct thermal conductance through the metamaterial is practically absent and the photovoltaic conversion of the transferred heat is not altered by the metamaterial.

1. Introduction

Over the last decade near-field thermo-photovoltaic (NF TPV) systems (e.g. [1]) are often considered in the modern literature as a promising tool for the field recuperation from high-temperature sources (industrial waste heat, car engine and exhausting pipe, etc.). The operation principle of NF TPV systems is based on the use of the evanescent spatial spectrum, i.e. on the use of the energy of infrared fields stored at nanometer distances from the hot surface. In presence of another body in the near vicinity of the hot surface the well-known photon tunneling phenomenon arises between two surfaces which leads to the dramatic increase of the heat transfer compared to the value restricted by the back-body limit [2]. This transfer can be enhanced if the hot medium, denoted as medium 1 in Fig. 1 (a), and the photovoltaic material, denoted in Fig. 1(a) as medium 3, both possess negative permittivity [1, 3]. The enhancement holds at a frequency where coupled surface-plasmon polaritons (SPP) are excited at the interfaces of media 1 and 3 [4].

In spite of their relatively high efficiency, NF TPV systems suffer strong technological drawbacks which restrict their applicability and industrial adaptation. First, it is difficult to create flat and clean surfaces of Media 1 and 3 separated with a nanogap (the roughness should be much smaller than the gap thickness d). Second, the cryogenic cooling or/and vacuum pumping is required for their operation since the thermal phonons suppress the photovoltaic conversion [1, 5] and the thermal conduction in the air is very high if d is smaller than the mean free path of the air molecules ($30 - 50$ nm) or comparable with it.

In the present paper we suggest a new paradigm for MTPV systems which should make such structures more competitive than NF TPV systems. We suggest to fill in the gap between media 1 and 3 with the metamaterial 2, performing the transformation of the evanescent spatial spectrum into propagating one. Metamaterials performing this manipulation with electromagnetic waves are, e.g., the so-called *indefinite media* [6]. For the infrared range such metamaterials can be performed as arrays of aligned carbon nanotubes (CNT) [7, 8]. Arrays of aligned metallic CNTs transform incident p-polarized infrared

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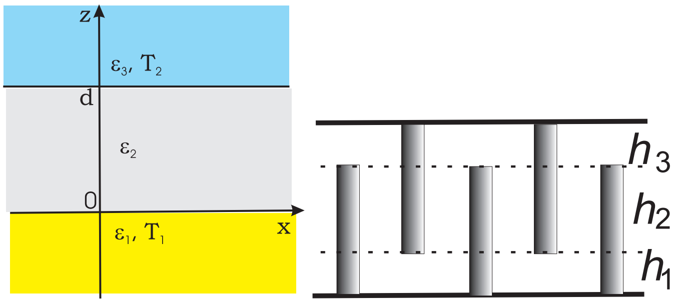


(a) (b)

Fig. 1: (Color online) (a) – Illustration to the general problem formulation. (b) – Interdigital arrangement of CNT allows to get rid of the thermal conductance.

waves (propagating and evanescent) into quasi-TEM waves propagating along CNTs with quite small decay. Unlike the SPP enhancement this effect holds over the whole mid IR range [7, 8].

2. Theory

The radiation heat transfer to medium 3 is calculated through the ensemble-averaged Poynting vector $\langle \mathbf{S}_z^{13} \rangle$ created by medium 1 at the input of medium 3 (plane $z = d$) minus the backward Poynting vector $\langle \mathbf{S}_z^{31} \rangle$ (calculated at $z = 0$) [2]. The spectral density of the total heat net transferred between medium 1 with temperature T_1 and medium 2 with temperature T_2 equals [2]:

$$q''_\omega = \int_0^\infty \Big[\langle \mathbf{S}_z^{13}(k_x, \omega, T_1) \rangle - \langle \mathbf{S}_z^{31}(k_x, \omega, T_2) \rangle \Big] k_x dk_x. \tag{1}$$

In (1) we neglect the heat radiation and absorption in medium 2. This approximation is justified for CNT arrays of small density (ratio diameter/period).

The incident Poynting vector created at the point $z = 0$ at the frequency ω by sources of thermal radiation distributed in medium 1 yields as follows:

$$\langle \mathbf{S}_z^{1}(k_x, \omega) \rangle = \frac{\varepsilon_1''(\omega)/2\pi}{\varepsilon_1 k_{1z} \mathrm{Im}(k_{1z})} (k_x^2 + k_{1z} k_{1z}^*) \Theta(\omega, T) + \text{c.c.} \tag{2}$$

where $\Theta(\omega, T)$ is the mean energy of the Planck oscillator

$$\Theta(\omega, T) = \frac{\hbar\omega}{\exp(\hbar\omega / k_B T) - 1}. \tag{3}$$

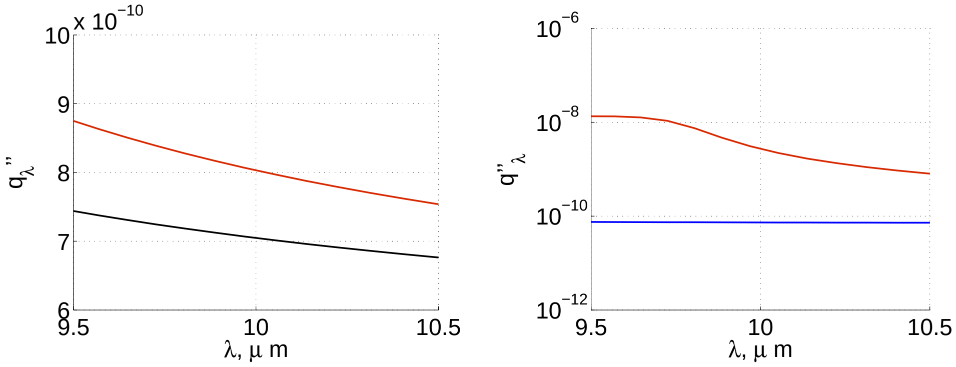
Here $\hbar$ is the reduced Planck constant, k_B is the Boltzmann constant, and T is the absolute temperature of the medium. The Poynting vector, transmitted from medium 1 to medium 3, is expressed as

$$\langle \mathbf{S}_z^{13}(k_x, \omega) \rangle = \frac{1}{2} \langle \mathbf{S}_z^{1}(k_x, \omega) \rangle |\tau|^2 \frac{Z_1^*}{Z_3^*} + \text{c.c.}, \tag{4}$$

where

$$Z_i = -E_{ix}/H_{iy} = \eta k_{iz}/k \qquad (i = 1, 2, 3) \tag{5}$$

and τ is the wave transmission coefficient which can be found for any media, filling the gap between bodies 1 and 3, using the transfer matrix method.



(a)

(b)

Fig. 2: (Color online) q'', calculated for the vacuum gap (blue) and the gap filled with CNTs (red), (a) – $d = 100$ nm, (b) – $d = 1$ μm (logarithmic scale).

3. Results and discussion

Let us assume that media 1 and 3 are heavily doped silicon (parameters of this material can be found in [3]) and have the same permittivity. Fig. 2 illustrates the dependence of the spectral density of the transferred heat $q''_\lambda(\lambda)$ (the evident analogue of q''_ω) for the case, when $d = 100\,\text{nm}$, $h_1 = h_3 = 10\,\text{nm}$ and for $d = 1000\,\text{nm}$, $h_1 = h_3 = 100\,\text{nm}$. The temperatures of the hot and photovoltaic surfaces were in both examples picked up as follows: $T_1 = 250^\circ$ and $T_2 = 0$. Then the maximal heat transfer corresponds to $\lambda_T \approx 9.5$ μm and $\langle \mathbf{S}_z^{31} \rangle = 0$. For the gap $d = 100$ nm the insertion of CNTs gives a modest overall enhancement about 20%. This is so because for the gap $d = 100$ nm the SPP enhancement (suppressed by CNTs) is still strong. However, for the gap $d = 1000$ nm, where the SPP enhancement is negligible, the total thermal transfer offered by CNTs exceeds by more than two orders the heat transfer through the vacuum gap. This effect opens a new door for the development of the MTPV systems.

To conclude: in this study we have shown the way to revolutionary increase the efficiency of microgap TPV systems inserting between the hot and the photovoltaic bodies a metamaterial which having the negligible thermal conductance converts the evanescent waves into propagating ones in a very broad range of spatial frequencies. We have shown that this conversion can hold over a wide frequency band and lead to a dramatic (2-3 orders) enhancement of the total thermal transfer across the micron gaps.

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