Supporting information

Artificial thermal flow control on thermoelectric device by tuning electrode absorptivity

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Supporting information

Supporting text S1-S4

Fig. S1-S3

Supporting text S1. Fabrication of the MA electrode

A polished Cu electrode whose width, length, and thickness are 4 mm, 6 mm, and 0.3 mm, respectively, was used as a substrate of the MA. After conventional cleaning with acetone and water, 150 nm-thick Ag and 60 nm-thick CaF_2 layers were deposited on a Cu electrode using thermal evaporator (SVC-7TS 80, Sanyu Electron Corporation). To fabricate Ag disks, hole patterns were drawn on a positive resist layer (ZEP520A, ZEON CORPORATION) formed on the CaF_2 and Ag layers deposited on a copper plate using electron beam lithography (JBX-6300FS, JEOL Ltd.), followed by development. A 100-nm-thick Ag layer was deposited on the patterned resist layer by thermal deposition. Ag disc arrays were obtained after the lift-off process. The diameter and pitch of the Ag disc were 1.75 and 3.0 μm, respectively. The MA arrays were fabricated at the center of the Cu electrode with an area of 2.1 × 2.1 mm^2 (490,000 units of the MA in the fabricated area). The film thicknesses of each layer were measured using a scanning electron microscope (SEM; SU-8000, Hitachi High-Technologies Corporation).

S2. Optical characteristics measurement of the MA, fullerene, and control electrodes

The reflection spectra of the MA arrays, fabricated on a copper electrode, were measured by microscopic Fourier transform infrared spectroscopy (FT/IR-6300, VIRT-3000, JASCO Corporation). The reference spectrum was recorded on a bare Cu electrode in the vicinity of the MA pattern. The absorption spectrum (Fig. 1c) was calculated using the 1 - reflectance. The reflection spectra of the fullerene and control electrodes were measured in the same manner.

S3. Experimental setup for measuring thermoelectric performance.

The configuration of thermoelectric device, length of wirings, setting positions of thermoelectric device in a chamber of the electric furnace greatly affect the thermoelectric performance of the thermoelectric device. In every experiment, we took the utmost care to ensure that the experimental conditions were consistent. Additionally, each experiment was repeated at least three times to obtain reproducibility. Additional information regarding the points of attention is provided below.

(i) Device configuration

As mentioned in the main text, in the thermoelectric device, the thermoelectric material and the opposite side electrode were kept unchanged, and only the electrode under investigation was modified. This allows us to focus solely on discussing the effect of the target electrode on the thermoelectric properties. Since the symmetry of the device also affects the thermoelectric properties, electrodes were attached symmetrically in devices.

(ii) Length of wirings

Wirings also play a role of thermoelectric material, meaning that the lengths of the left and right wirings inside the furnace chamber must be same. We controlled the length of the Au and Cu wirings same in all experiments. Furthermore, the Cu wires were bundled and controlled to pass through the same location within the furnace chamber.

(iii) Setting positions of a thermoelectric device in a chamber of the electric furnace

The setting positions of the thermoelectric device in a furnace chamber greatly influence on thermoelectric performance. We precisely adjusted the position of the device to ensure that the distance from the sidewalls of the electric furnace to the electrodes at both ends of the device was equal. Similarly, the position of the carbon pot was carefully controlled to align its center with the center of the device.

S4. Thermoelectric simulation

In the thermoelectric simulation, the calculated power density, which corresponds to the electromagnetic energy density absorbed by the material, is given to each material such as the MA and control electrode every second to simulate the thermal distribution across the thermoelectric device by considering local heat generation at each material. The power density is the total energy absorbed by the material over given area and can be expressed in units of W/m^3. These settings are required because all materials consisting of the device generate local heat depending on its absorption properties. This means that the thermal distribution across the thermoelectric device was formed depending on the local heat temperatures generated on each element. The initial temperature of the thermoelectric simulation was 364.15 K, which is equal to the measured environmental temperature.

In the simulation model, the metamaterial thermoelectric device was surrounded by an airbox with a size of $2.5 \times 2.5 \times 2.5$ cm^3, which corresponded to the air space inside the carbon pod. Furthermore, to allow heat transfer from the inside of the airbox to the outside, a larger airbox with a size of $50 \times 50 \times 50$ cm^3 was placed to cover the inner airbox.

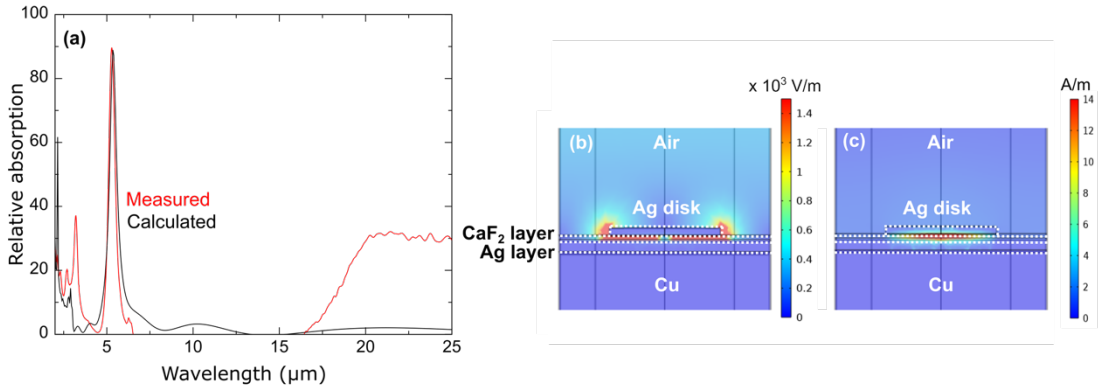

Figure S1. (a) Comparison of the calculated and measured relative absorption spectra of the MA. (b) Electric and (c) magnetic field distributions of the MA at wavelength of 5.3 μm, with X-Z plane.

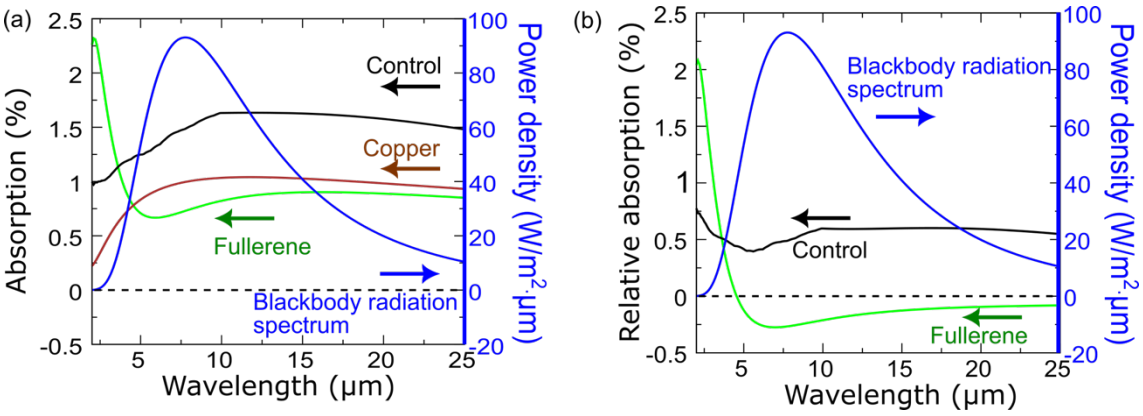

Figure S2. (a) Comparison of calculated absorption spectra of fullerene, control electrode, bare copper electrodes, and with a blackbody radiation spectrum calculated at 373 K. (b) Calculated relative absorption spectra of the fullerene layer and a control electrode with a blackbody radiation spectrum at 373 K. The relative absorption was calculated by subtracting the calculated absorption spectrum of Cu from the absorption spectra of fullerene and control electrodes. This calculated relative absorption was obtained through the same process as the relative absorption obtained experimentally.

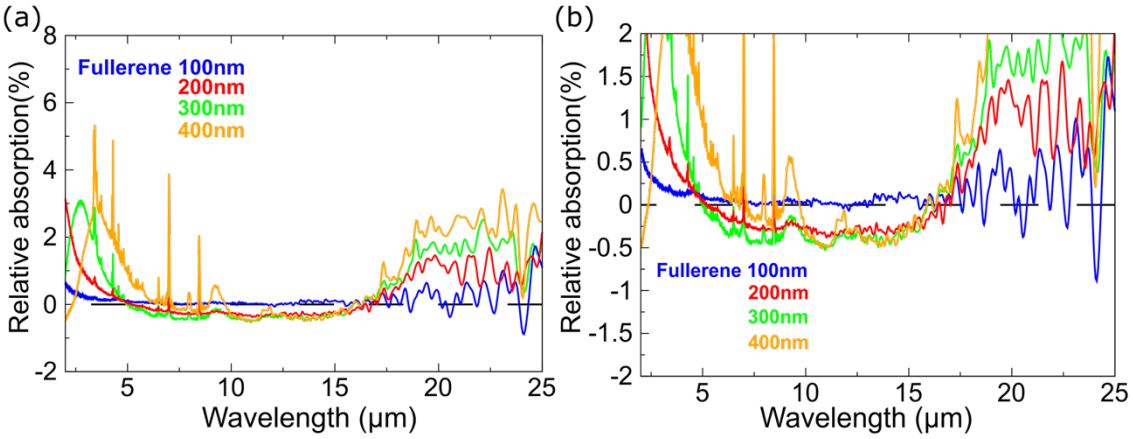

Figure S3. (a) Measured relative absorption spectra of fullerene layer with thicknesses of 100 (blue line), 200 (red line), 300 (green line), and 400 nm (orange line), respectively. (b) Enlarged absorption spectra.