Photo-thermal effect within plasmonic absorption metamaterials in infrared region

Yongqian Li, Chenglin Zhang, Xiaolun Xu

Key Laboratory of Micro/Nano Systems for Aerospace of Ministry of Education, Northwestern Polytechnical University, Xi’an 710072, China
*corresponding author: liyq@nwpu.edu.cn

Abstract-The energy-conversion process and photo-thermal effect within a plasmonic absorber metamaterials (PAM) were investigated theoretically using the Poynting theorem. The Ohmic loss and dielectric loss were calculated to estimate the amount of heat energy produced. The heat-generation within the PAM was studied numerically. From the microscopic details, the heat-generation owing to the electric current accounts for the majority of the energy conversion, while the magnetic resonance plays a negligible role. The strong field confinement and redistribution within plasmonic absorber metamaterials (PAM) guides in a subsequent thermal-detection design.

The electromagnetic absorption and tunability of recently emerging perfect-absorber metamaterials (PAMs) have been demonstrated to potentially enable electromagnetic-wave detection at nearly any frequency, ranging from the terahertz to infrared [1,2] and even visible light range. One key problem for PAMS is the conversion of electromagnetic energy into other types of energy such as the transformation of terahertz waves into infrared radiation [3], photocurrent [4], and thermo-mechanical energy. Photothermal effects play a critical role in the detection of electromagnetic radiation [5]. The photo-thermal effect associated with multiplex resonant electromagnetic wave passing through the PAM medium provides insight into the energy conversion processes inside the nanostructure [6]. The typical dielectric layer, as an energy dispersive medium, is sandwiched between the top metallic periodic arrays and the bottom conducting ground metallic plane, as shown in Figure 1. In conjunction with the transmission blocking of the thick metallic film, the incident electromagnetic energy was effectively confined within the dielectric layer, thereby enabling nearly perfect absorption.

Figure 1. Schematic of side view (a) and the top view (b) for proposed plasmonic absorber metamaterials.

The ultimately absorbed energy in each spatial volume at the frequency component is integrated as,

$$\int_{V_i} (Q_e + Q_m) dV = \frac{1}{2} \omega \int_{V_i} \left( \epsilon_0 \text{Im} \varepsilon(\omega) |E|^2 + \mu_0 \text{Im} \mu(\omega) |H|^2 \right) dV$$

(1)

Where $V_i$ represent the spatial volume of the metallic ground layer, the dielectric layer, and the top metallic
resonators layer. As shown in Figure 2, the Poynting energy distribution displays clearly discrete patterns in one unit cell, and the local enhanced fields were highly confined symmetrically at the regions around the metal gaps or the tips of the resonators.

The photothermal heating process was numerically simulated following the heat transfer equation. Thermal profile and temperature distribution within the PAM structure are summarized in Fig.3. Figure 3(a) shows that it is only 2.0 ns after the beginning of pulse irradiation, the temperature within the top metal resonator reaches to its highest value about 680K. However, the maximum average temperature within the ground metal film is only 330K, although only 50 nm separated away from the top metal resonator. It is significantly observable in Fig.3 (b) that there are two huge gradient of temperature at the interfaces between the metal and dielectric layer, confirming the fact that the heat-generation occurs mostly within metal materials due to the Ohmic loss.

![Figure 2](image1.png)

**Figure 2.** Concentration and redistribution of the electromagnetic Poynting Field (|\(\mathbf{P}\)|\(^2\)) within one unit cell excited by resonant wavelengths of (a) 7.20 μm, (b) 2.75 μm, and (c) 3.40 μm.

![Figure 3](image2.png)

**Figure 3.** Thermal effects within the PAM structure subject to a pulsed electromagnetic source. (a) Thermal transient response within three layers; (b) Temperature spatial distribution within a unit cell of PAM structure.

Authors acknowledge the support from the National Natural Science Foundation of China, (NSFC-No.51175436), and the 111 projects from Chinese Ministry of Education (No.B13044).

**REFERENCES**