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Outline of the thesis

To use selective far- and near-field radiation transfer between a radiation source and a thermophotovoltaic (TPV) cell with optical metamaterials, it is necessary to clarify the electromagnetic phenomena of the metamaterials employed. The main objectives of this thesis are to:

1. Design an infrared emitter as a hyperbolic metamaterial for near-field radiation transfer and develop an explanation of the resonant mode of near-field radiation, and,

2. Propose a promising metamaterial-TPV cell using an analytical model for a metamaterial with perfect absorptance only for a specified wavelength of far- or near-field radiation.

In the first chapter, the background and the significance of TPVs are reviewed and summarized. Moreover, several important approaches to improve the power density of TPVs are also introduced. In Chapter 2, the radiation characteristics of a square pillar array structure, which is a possible hyperbolic metamaterial, are investigated using a finite difference time domain (FDTD) method. Two materials, aluminum doped zinc oxide (AZO) and tungsten are applied for the material of the pillar array to utilize strong near-field radiation originating from surface plasmon polariton resonance (SPPR) and the hyperbolic resonant mode in a pillar array. Through numerical simulation of the electromagnetic field around a pillar array structured emitter and receiver using FDTD, the physical phenomena that controls radiation flux is revealed. Using the knowledge obtained through numerical simulations, the geometric parameters of a pillar array structure required to enhance spectral radiation flux are shown. In Chapter 3, a metal–semiconductor–metal (MSM) multilayer is proposed as a promising structure for a metamaterial-TPV cell. In the MSM multilayer, the thickness of a photovoltaic semiconductor, such as GaSb, is reduced until a several hundred nanometer thick depletion layer remains and a thin GaSb layer is sandwiched between two nano-structured layers of gold electrodes. The absorptance of the MSM multilayer is evaluated using numerical simulation and the feasibility of a MSM multilayered TPV cell for far-field radiation is discussed. Moreover, several new equivalent models to describe the resonant mode of MSM multilayer are shown. In Chapter 4, the pillar array structured emitter presented in Chapter 2 and the MSM multilayered TPV cell discussed in Chapter 3 are combined to enhance the efficiency of a TPV system using near-field radiation. For each resonant mode of the pillar array structure and the MSM multilayer, whose mechanisms are different, the potential for the enhancement of near-field radiation transfer is discussed. Additionally, promising combinations of emitters and TPV cells to enhance the spectral radiative heat transfer within limited band of angular frequencies are proposed. Last, key findings and contributions in this thesis are summarized and perspectives for future research are presented in Chapter 5. Moreover, discussion of the validity of the numerical simulations used in this study, the benchmark tests of MPI protocol introduced into the current simulation program, the effect of error in the refractive index of GaSb and derivations of formulas in this thesis are included as appendices.