PROJECT ABSTRACT

The objective of this research is to establish a computational toolbox for designing metamaterials, with user-defined thermal radiative properties, beyond the effective medium theory. This will be accomplished by direct calculation of near-field thermal emission via a novel approach called the Thermal Discrete Dipole Approximation (T-DDA). The establishment of thermal metamaterials with unique designer properties will expedite the development of technologies such as infrared cloaking and nanoscale-gap thermophotovoltaic (nano-TPV) power generation.

Metamaterials’ electromagnetic properties are usually predicted via the effective medium theory, where a heterogeneous medium is conceptualized as homogeneous with effective electric permittivity and magnetic permeability. When considering the near-field electromagnetic spectrum emitted at a distance smaller than the size of the meta-atoms or their separation distance, approximating a heterogeneous layer as homogeneous may lead to significant errors. Current methods do not allow direct calculation of near-field thermal emission by metamaterials made of complex three-dimensional (3D) inclusions such as split-ring resonators and dielectric particles. Additionally, the effective medium theory does not account for all the microscopic interactions between the inclusions, the host medium and electromagnetic waves. When directly calculating near-field thermal emission by metamaterials, all the complex interactions between the different material constituents are accounted for.

The proposed project is radically different from the state-of-the-art, as it will provide for the first time a computational toolbox for designing thermal metamaterials made of 3D arbitrarily-shaped inclusions beyond the effective medium theory. The research program is divided into three tasks:

1. Implementation of a novel computational method called the T-DDA for modeling near-field radiative heat transfer in 3D complex geometries, 2. Application of the T-DDA to direct calculation of near-field thermal emission by metamaterials and assessment of the validity of the effective medium theory, and 3. Design of metamaterials maximizing nano-TPV power generator performances. The T-DDA is based on discretizing bodies into electric point dipoles. As such, the T-DDA can accommodate any type of complex-shaped objects, and will allow near-field heat exchange predictions between bodies much smaller and much larger than the wavelength. Task 1, to be completed in years 1 and 2 of the project, will lead to an open-source code for modeling near-field thermal radiation problems in complex 3D geometries. In years 2 and 3, Task 2 will be devoted to direct calculation of near-field thermal emission by metamaterials made of 3D inclusions. These predictions will allow determining the conditions of the applicability of the effective medium theory for thermal metamaterial design. Task 3, to be completed in year 3, is devoted to the design of metamaterials maximizing nano-TPV performances. This will be done by using the T-DDA in conjunction with a coupled charge and heat transport model. A genetic algorithm will be employed in order to design metamaterial-based radiators maximizing near-field power enhancement in nano-TPV devices. The application of metamaterials to nano-TPV power generators will allow low temperature waste heat recovery in a variety of electronic devices, such as cell phones and photovoltaic cells.

This project will promote training and learning via the involvement of a PhD student in the research activities. Additionally, the outcome of this research will be integrated into a Nanoscale Heat Transfer class offered to both undergraduate and graduate students. The project will have major impacts in metamaterial design, thermal radiation at the nanoscale and low temperature waste heat recovery, and will pave the way to the development of novel metamaterial-based technologies such as nano-TPV power generation and infrared cloaking to name only a couple.