Broad Area, Selective-Emitters for High Temperature Operation

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***Abstract*—Thermophotovoltaic and rectenna devices can be greatly improved by frequency-selective emitters, which narrow the emission spectrum of a heat source to couple to the most efficient operating point of the device. We have simulated an alumina and titanium emitter using a Fabry-Perot design which is intended for use with thermal energy converters operating in the near to mid infrared region.**

Keywords—thermophotovoltaic; TPV; emitter; infrared; Fabry-Perot; rectenna

I. INTRODUCTION

For more than a century we have generated electrical power largely in a singular fashion: generate heat → boil water → create pressurized steam → turn a turbine → create electricity. For the 21st century, a simpler solid-state system (generate heat → convert to electricity) is highly desirable and could mean higher conversion efficiencies and more reliability. These systems are heat source agnostic: fossil fuels, industrial waste heat, solar concentrators, and radioisotope sources can all provide heat to be converted into electricity. Thermophotovoltaic (TPV) and rectenna systems both directly convert infrared photon emissions into electricity – Fig. 1. Both can be built to exceed the conversion efficiency of thermoelectric systems, which is the legacy solid-state technology. Additionally, both can benefit greatly from the use of a frequency selective-emitter. A selective-emitter narrows the emission spectrum to only emit the wavelengths that are easily converted.[1] In a TPV system, an emitter tuned for the bandgap of the TPV cell maximizes power conversion while reducing unwanted heating caused by photons that do not align well with the bandgap. The incorporation of a selective-emitter in a rectenna system allows for a simpler antenna design and eases impedance matching between the antenna and the rectifying diode.

Fig. 2 shows a simulation of an emitter designed to isolate emission around a peak wavelength of five microns. The emission from a 300°C blackbody is shown for comparison. A well designed selective-emitter allows the power converter to operate at peak efficiency and an ideal emitter technology can create emitters tuned to any desired wavelength.

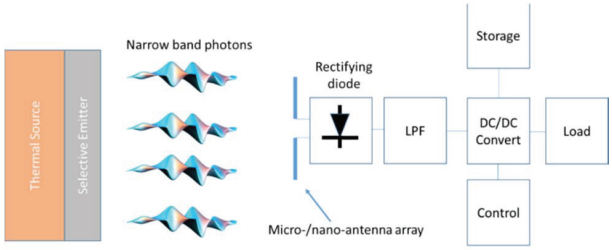

Fig. 1: A schematic layout for an efficient infrared rectenna system. A selective emitter, commonly used in thermophotovoltaic systems, is used to narrow the emission spectrum and, therefore, simplify the rectenna design.

II. FABRY-PEROT EMITTER

Our research group has extensively explored a number of emitter technologies.[1]–[5] Unfortunately, many of these emitters require e-beam lithography to fabricate, which is not applicable for the large areas (>1cm^2) needed to convert the energy being discussed. We are currently working to expand the application possibilities of Farby-Perot type emitter surfaces.[6] This technique employs two metal layers with a dielectric layer between to form a Fabry-Perot cavity - Fig. 3. The top metal layer is very thin, only a few nanometers, allowing transmission at the resonant wavelength. The resonant wavelength is determined by the thickness and index of refraction of the dielectric layer, and the width of the emission peak is determined by the thickness of the top metal layer, allowing us to engineer the power density and efficiency of the system.

We are currently testing new material combinations that will allow this technique to be used at a variety of wavelength regions from near to far infrared. Since our primary interest is thermal power conversion, we are also testing for performance and durability at high temperature. Some selective-emitters employing nanostrucured materials have shown poor durability at high temperatures due to distortion of the nanostructures.[1]–[5] The simpler fabrication of the Fabry-Perot design is inherently more robust, but careful selection and testing of materials and fabrication methods is still required. The materials selected need to have the same

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thermal expansion coefficients and not be miscible or oxidize in the temperature ranges.

Emitters for a 200°C to 1200°C temperature range, 2µm to 6µm wavelength range, require dielectric materials suitable for optical performance in this regime. Durability at these temperatures is addressed by using metals with high melting points, often refractory metals. Our research group has worked with high temperature metals for previous emitter designs, and the use of platinum or iridium on alumina has proved particularly thermally robust in prior experiments. The choice of material combinations is limited somewhat by the need to match the thermal expansion coefficients of the dielectric and metal. These devices are intended operate during extreme thermal cycling, and a significant mismatch in thermal expansion would cause separation of material layers.

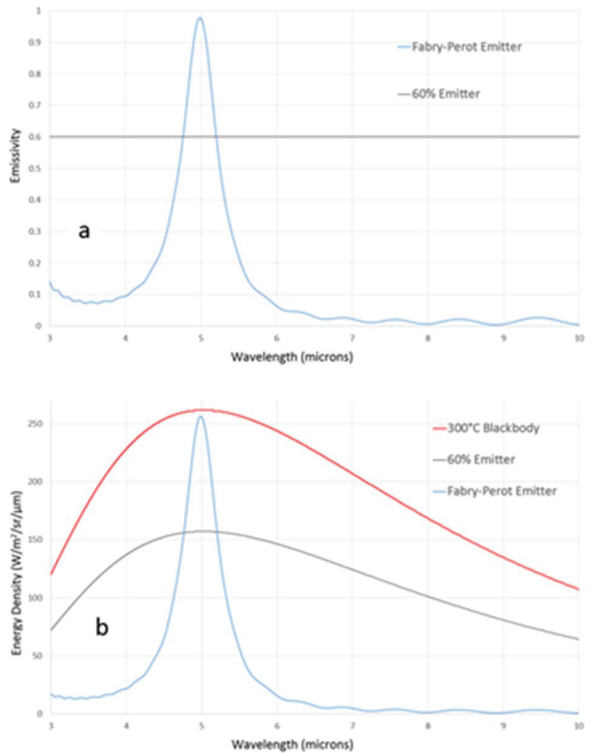

Fig. 2: a) simulation of Fabry-Perot selective emitter tuned for 5 micron emission (blue), and a flat 60% emissivity surface (gray) which approximates a heat source without a selective emitter; b) emission from a 300°C blackbody with a Fabry-Perot emitter compared to a source with no emitter. The selective emitter is designed to focus an emission spectrum at the most efficient operating point of an energy conversion device.

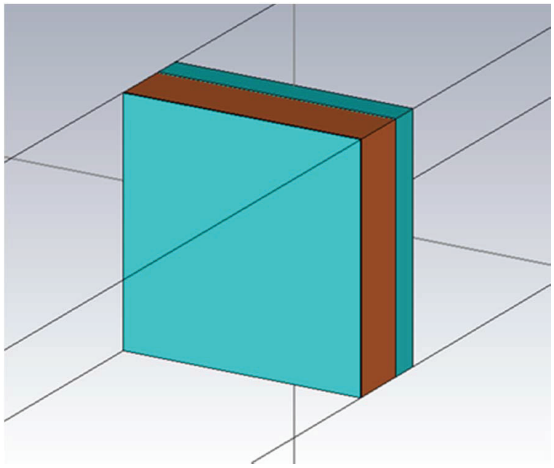

Fig. 3: A Farby-Perot cavity emitter is formed from two metal layers and a dielectric layer. The top metal layer is made very thin to allow transmission at the resonant frequency of the cavity.

III. Simulation Results

The first material system we are investigating uses aluminum oxide as the dielectric layer. Titanium, chromium, and iridium were chosen as potential mirror layers because they have coefficients of thermal expansion similar to that of alumina. Our simulations indicate that titanium will produce a device with the desired characteristics. These simulations were performed with CST Microwave Studio using the time-domain transient solver. Based on current results, only titanium demonstrates the desired narrow emission peak for maximum conversion efficiency. Fig. 4 and 5 show the simulation results for the alumina and titanium device with varying layer thicknesses. Fig. 6 is an alumina and titanium device optimized to couple to a 500°C blackbody – spectral peak at 3.75 microns. An alumina window layer was added to prevent oxidation of the top titanium layer - Fig. 7.

Emitters are currently being fabricated using DC magnetron sputtering. A tool with two magnetron sources allows complete fabrication without breaking vacuum. A reactive sputtering process is used to deposit the oxide layer. Initial testing is being performed using an infrared spectrometer to measure absorption across the near- and mid-infrared spectrum. Additionally, the samples will be characterized with an infrared ellipsometer. Thermal durability will be tested extensively to ensure that the device can operate in real world conditions. Samples will be characterized before and after heating to check for thermal robustness, as well as directly measuring emission at temperature.

Simulations predict that a high temperature selective-emitter can be made with alumina and titanium. We are currently working to fabricate and test this design. After this first round of design and testing, we expect to develop other material combinations to accommodate a range of frequency regions. Our goal is not only to develop a high performance emitter, but to establish guidelines for selecting materials and fabrication techniques for new device designs.

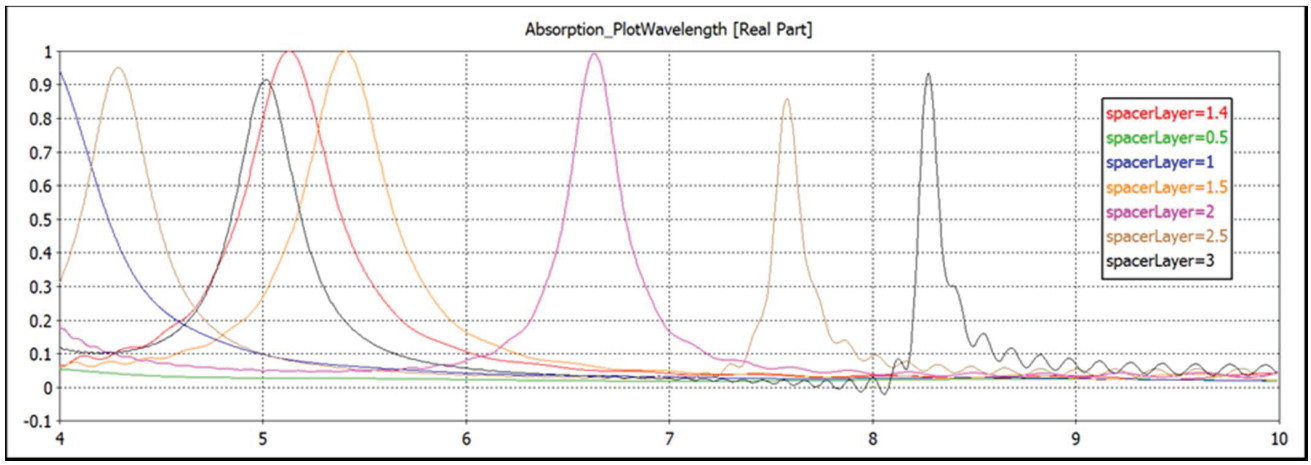

Fig. 4: Ti and Al2O3, varying dielectric thickness. Top mirror layer is 28nm.

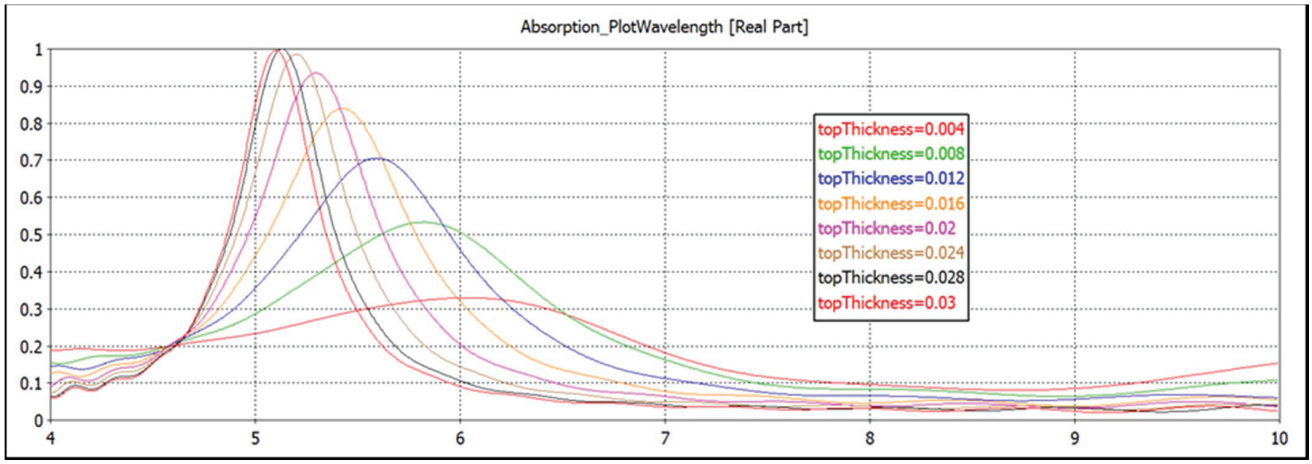

Fig. 5: Ti and Al2O3, varying top mirror thickness. Al2O3 layer is 1400nm.

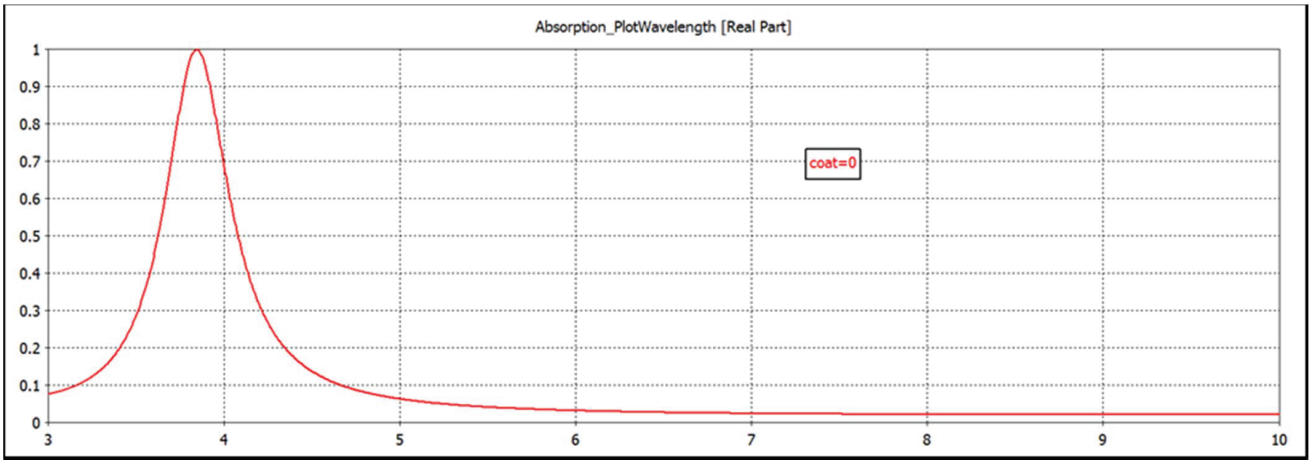

Fig. 6: Ti and Al2O3. Al2O3 layer is 1000nm. Top mirror is 36nm.

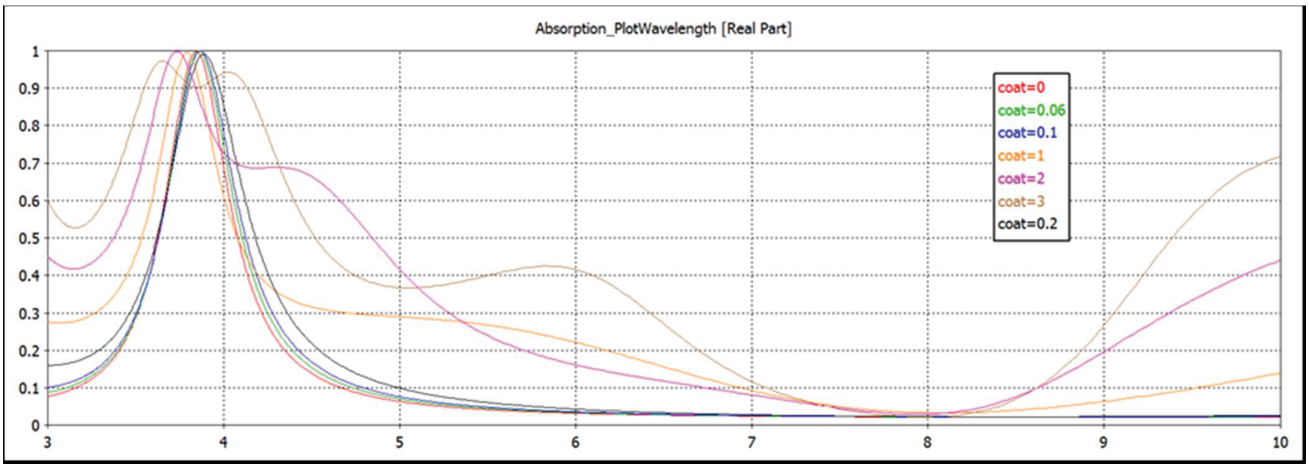

Fig. 7: Ti and Al2O3, varying window layer thickness. Al2O3 layer is 1000nm. Top mirror is 36nm. Window layers thinner than 100nm have little effect on performance.

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