Investigation of THz Thermal Emission from Electromagnetic Crystals

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Abstract— Thermal emission at THz frequencies from an electromagnetic (EM) crystal is investigated both theoretically and experimentally. Because the photon density of states (DOS) of an EM crystal becomes redistributed, a large enhancement in the thermal emission within a desired frequency range may be possible. Band diagrams and DOS of both silicon and Tungsten woodpile structures are calculated and their thermal radiation intensity estimated. Theoretical results show that an enhancement factor of 12 around 360 GHz, compared with normal blackbody radiation, could be achieved for the silicon woodpile structures. A silicon woodpile structure was designed and fabricated. Thermal emission measurements were conducted by Fourier transform spectroscopy (FTS).

I. INTRODUCTION AND BACKGROUND

THz combines some of the advantages of both the microwave and infrared (IR) spectra, providing coverage in IR-blind conditions while offering higher bandwidth and resolution than microwave frequencies. THz technology is blooming with potential applications in contraband detection, tumor recognition, DNA sequencing, tissue imaging, radar and communications over the past few years [1-2]. However, the lack of high performance and low-cost THz power sources is one of the most challenging issues of THz applications. We introduce a novel THz source concept based on thermal radiation in the presence of EM crystals (also known as photonic crystal or photonic band gap structures in optics). Theoretical and experimental results are reported and give promising indications that carefully designed EM crystal thermal radiators may be useful in thermal imaging and identification applications and enable a new type of low cost and high performance THz source [3].

The thermal power radiated by a normal blackbody at temperature T within the frequency range *f* to (*f*+*df*) per unit volume is well defined by Planck's equation [4]:

$$E(f)df = \rho(f)\cdot\frac{hf}{e^{hf/kT}-1}\cdot df = \frac{8\pi f^2}{c^3}\cdot\frac{hf}{e^{hf/kT}-1}\cdot df \qquad (1),$$

where $\rho(f)$ is the photon density of states, $h = 6.626e\text{-}34\ m^2\ kg/s$ is the Planck constant, *hf* is the individual photon energy, and one over the denominator is the Bose-Einstein distribution representing the statistics of photons. In Eq. (1), all other quantities are fixed except the photon DOS. To the first order (assuming ideal coupling to the external environment), thermal radiation emitted by an object has a linear relationship with its photon DOS. Thus, the idea of modifying the normal blackbody DOS with a 3D EM crystal arises naturally. With the presence of an electromagnetic band gap (EBG), a 3-D EM crystal can drastically modify the distribution of the photon DOS in different frequency ranges. Within the EBG of an EM crystal, spontaneous emission is completely forbidden because there is no photon state in that frequency range which can couple with an atomic transition, yielding a photon DOS that is zero. The existence of an EBG will result in a shift of the emission energy from the forbidden frequency range to another adjacent EM band-pass frequency range. This in turn causes an enhanced DOS to emerge and hence an enhanced emission rate. This phenomenon is often known as the "anti-crossing" effect.

II. RESULTS

Because of its relatively simple geometry and the ease of fabrication among the 3-D EM crystals, a silicon woodpile structure (WPS) was selected for our initial study. A schematic drawing of a WPS is shown in Figure 1 [5]; it consists of a unit cell containing *4* layers of infinitely long silicon square rods stacked with a periodicity *D*. Within the unit cell, the rods in each layer are distributed with the same periodicity *d*; and the adjacent layers that have the same rod orientation are shifted with respect to each other by *d/2*. Each rod has a height *h = D/4* and a width *w = h*.

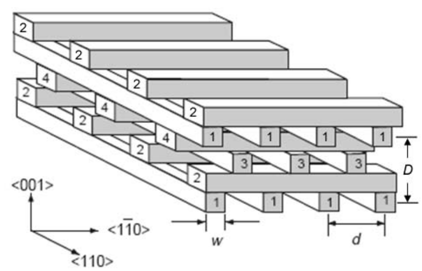

Figure 1. Schematic drawing of a woodpile EM crystal.

A silicon WPS with a band gap around 200 GHz was designed. The band diagram and the photon DOS for this silicon WPS was calculated first by using the MIT MPB code and then verified by using Ansoft's HFSS Eigensolver. The thermal radiation intensity was then calculated using Eq. (1) and compared with the normal Planck distribution. The calculated thermal emission enhancement of the WPS over that of a normal blackbody is shown in Figure 2. The plot explicitly shows a complete band gap from around 175 GHz to 216 GHz, i.e., there is no thermal energy radiated from the WPS in that frequency band. There are several thermal radiation power enhancement peaks observed, for example, around 148, 163, 254, 283, 364, 393, 415 and 448 GHz. The power enhancement factor is as high as 11.8 at the 364 GHz peak, which means there is more than 1080% power output increase at 364 GHz over the normal blackbody value.

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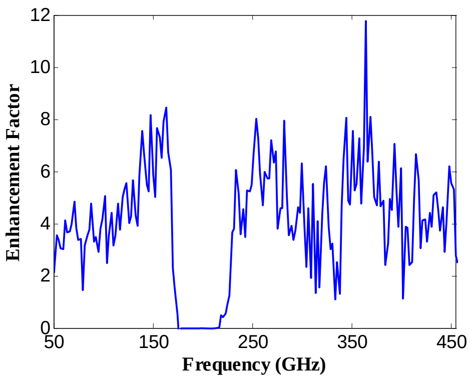

Figure 2. Calculated thermal emission enhancement of the silicon WPS over the normal blackbody.

The designed silicon WPS was fabricated using a robust mechanical layer-by-layer dicing process [6]. A series of grooves were cut into both the front and back faces of a silicon wafer by using a diamond dicing saw. One wafer thus makes up one half of the WPS unit cell, and the complete WPS is then assembled by stacking many wafers together with the help of pre-registered alignment marks.

Characterization of this EBG sample at THz frequencies was carried out with the THz Time-Domain Spectroscopy (THz-TDS) transmission approach. The TDS measured and HFSS simulated transmission results along the sample stacking direction are shown in Figure 3. Not only does the predicted 200 GHz band gap match well, but also the predicted secondary band gap near 310 GHz and the various predicted transmission peaks match quite well with the measured data. The good agreement between the measured and simulated transmission results verifies the WPS design and fabrication procedures.

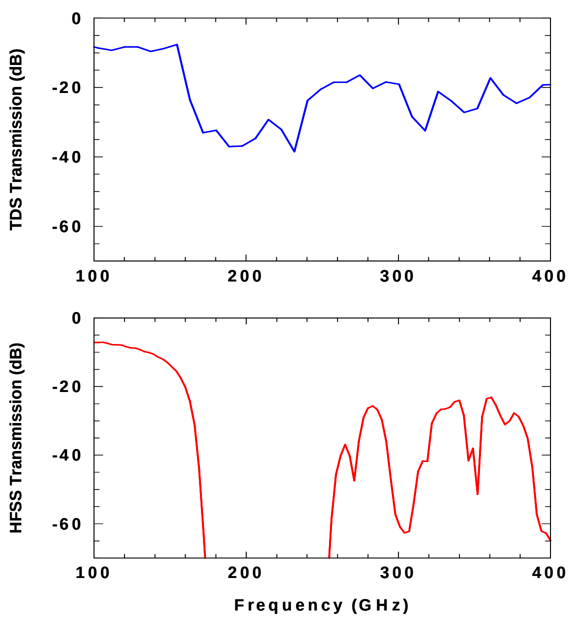

Figure 3. Transmission responses (normal incidence) of the silicon WPS sample: (top) THz time-domain spectroscopy (TDS) measurement, (bottom) HFSS Simulation.

To experimentally study the predicted THz thermal radiation enhancement, direct thermal emission measurements of the fabricated silicon WPS were performed using a Beckman FS-720 Fourier Transform Spectrometer (FTS) with a frequency range from 100 GHz to 3.6 THz. The measured thermal emission resulting from the WPS and from a radiation absorption material (RAM) acting as a blackbody at 85ºC are plotted in Figure 4. Experimentally measured enhancements of the WPS thermal emission over the control blackbody sample can be observed around 110, 146, 165, 288, 362 and 440 GHz. These enhancement peaks match up qualitatively well with the predicted enhancement peak positions given in Figure 2 and listed previously. Statistical error bars based on multiple measurements also verify that the measured WPS emission enhancements over the control blackbody sample are repeatable observations. These results qualitatively justify the prediction of the thermal radiated power using the DOS calculation. They are also good indications that an EBG emission source with enhanced THz thermal radiation may be feasible.

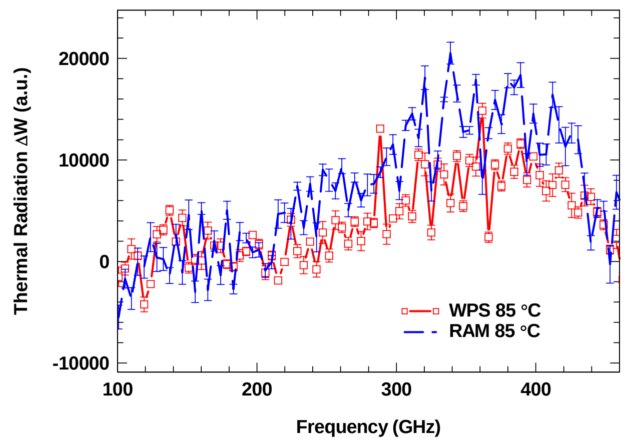

Figure 4. The thermal radiation differential spectra for the RAM (dashed) and the WPS (squares) samples at 85ºC. The error bars are statistical.

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