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Alves, Fabio
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Fabio Alves, * Brian Kearney, Dragoslav Grbovic, and Gamani Karunasiri
Department of Physics, Naval Postgraduate School, 833 Dyer Rd, Monterey, California 93943, USA
jdalves@nps.edu

Abstract: In this article we report on metamaterial-based narrowband thermal terahertz (THz) emitters with a bandwidth of about 1 THz. Single band emitters designed to radiate in the 4 to 8 THz range were found to emit as high as 36 W/m² when operated at 400 °C. Emission into two well-separated THz bands was also demonstrated by using metamaterial structures featuring more complex unit cells. Imaging of heated emitters using a microbolometer camera fitted with THz optics clearly showed the expected higher emissivity from the metamaterial structure compared to low-emissivity of the surrounding aluminum.

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1. Introduction

The continued interest in terahertz (THz) research demands high power sources and sensitive detectors [1–6]. The energy of photons in THz range of interest (1-10 THz) is relatively low (4-40 meV) requiring complex device architectures for generation [3] and detection [5] at these frequencies. Imaging in this spectral range generally requires an illumination source due to the lack of appreciable background thermal radiation at these frequencies [7, 8]. A number of different techniques have been employed to generate THz radiation [9] with varying power levels. However, the most promising approaches able to generate appreciable power include free electron lasers (FELs) [10] and THz quantum cascade lasers (QCLs) [3, 6, 11], albeit with some drawbacks. For example, FELs generate high power at the expense of requiring a large footprint while the QCLs are compact but only operate at cryogenic temperatures. More recent attempts on THz generation at room temperature include the use of resonant tunneling diode based oscillators [12] and nano-electrodes in a photoconductive photomixer [13], where the generated power levels are still in the microwatt range. An alternative approach to generate THz is to use a heated object with its emissivity tailored to match the specific THz frequency band of interest. The thermal generation of narrowband infrared by controlling emissivity has been demonstrated by using periodic array of holes [14], nano-amorphous carbon [15] and metamaterial structures [16, 17]. In this paper, we report on the realization of narrowband (~1 THz) thermal THz emitters based on metamaterial structures designed to emit at specific frequencies in the 4 to 8 THz spectral region.

2. Design and fabrication

The metamaterial emitters are comprised of a periodic array of Al square unit cells separated from an Al ground plane by a SiO$_2$ layer as schematically illustrated in Fig. 1(a). Each Al layer is approximately 100 nm thick and the thickness of the SiO$_2$ layer is about 1.6 μm. The dimensions of the Al squares were selected to tune the emissivity (or absorptance) to the desired THz frequency. The design of metamaterial emitters were carried out using 3D finite element modeling COMSOL multiphysics software, where the emissivity characteristics of the structures were simulated for varying Al square sizes. Due to the periodicity of the metamaterial structures, a unit cell as shown in Fig. 1(a) was used in the simulation. The field distribution is calculated for a normally incident plane wave polarized along one of the edges of the Al square. Periodic boundary conditions are applied to the lateral faces of the unit cell.

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The reflected power as a function of THz frequency (one watt incident power for all frequencies) is calculated by integrating the power flow on the layer boundary, while transmission is assumed to be zero since the ground plane thickness is greater than the skin depth of aluminum in this frequency range (about 80 nm for aluminum at 4 THz). The index of refraction of SiO\textsubscript{2} at THz frequencies was taken from [18, 19] as 2.0. The extinction coefficient is frequency dependent in this range and it was taken from [20], varying from 0.025 (4 THz) to 0.08 (8 THz). The conductivity of Al was measured as $1 \times 10^7$ S/m. Three metamaterial emitter structures with Al square dimension of 9, 13, 17 μm were fabricated on a silicon substrate using standard microfabrication techniques. The Al ground planes, 100 nm thick, were deposited using e-beam evaporation. The dielectric SiO\textsubscript{2} films 1.6 μm thick was deposited using plasma-enhanced chemical vapor deposition (PECVD) followed by e-beam deposition of another layer of Al film, 100 nm thick. Finally, the square arrays were patterned, using plasma sputter etch. Figure 1(b) depicts an optical micrograph of a fabricated metamaterial structure (sample C) showing the periodic array of Al squares. The periodicity of all three samples was kept constant at 21 μm as indicated in Fig. 1(b).

Fig. 1. Metamaterial structures comprised of periodically distributed Al squares placed on top of a SiO\textsubscript{2} film backed by an Al ground plane, used for single band THz emitters. (a) Schematic diagram of a periodic unit cell used for finite element simulation. (b) Optical micrograph of a fabricated emitter showing the periodic array of Al squares. The inset shows the dimension of Al squares of each sample.

3. Experimental results

Before measuring the THz emission from the samples, absorption characteristics were determined through reflection spectra using a Fourier transform infrared spectrometer (FTIR Nexus 8700) fitted with a globar source, a Si beamsplitter, a pyroelectric detector and appropriate accessories. The reflectance (R) was measured with the FTIR beam incident at 15° from the normal of the absorber arrays and the absorptance spectrum of each sample was obtained by evaluating (1 – R), since transmittance is zero. Figure 2 shows the absorptance spectra of the three samples in the 3 to 10 THz range revealing clearly separated narrow absorption peaks that move to higher frequencies as the dimension of the Al squares decreases. It was observed that the peak emission frequency depends on the inverse of the size of the aluminum squares (1/\(a\)). The explanation of this phenomenon is still under debate and there are different theoretical approaches. The physical mechanism of the absorption effect has been explained by the excitation of localized electromagnetic resonances, especially the magnetic resonance was evidence by the anti-parallel surface currents excited in the two metallic layers [21]. On the other hand, investigation using interference models have shown that the anti-parallel surface currents are reproduced by interference and superposition and there is no magnetic coupling between the metallic layers [22]. In addition, cavity resonance [23], Fabry-Pérot resonance [24] and transmission line [25] models have been proposed. Qualitatively, the interaction of electromagnetic radiation with a metamaterial structure can be described using an equivalent LRC resonator circuit [26] with resonant frequency.
\( = \frac{1}{\sqrt{LC}} \). Since the capacitance depends on \( a^2 \), an inverse linear dependence on size (a) is expected for the resonant frequency, which agrees with the experimental observations.

Fig. 2. Spectral absorptance of the metamaterial samples A, B and C. Solid lines represent the measured absorptance with peaks at 4.1, 5.4 and 7.8 THz respectively. Dashed lines represent the finite element simulation results.

It can be seen in Fig. 2 that the absorptance falls from 0.98 (sample A) to 0.85 (sample C), which agrees with that of the COMSOL finite element modeling as indicated by the dashed curves. This is expected due to the use of the same SiO₂ layer thickness and structure periodicity for all three samples while in our design, the parameters are selected to maximize the absorption for the sample A [19, 20]. However, by using the appropriate oxide thickness and structure periodicity, it is possible to obtain absorptances close to unity for the samples B and C [27].

The narrowband absorption spectra of the metamaterial structures shown in Fig. 2 suggest that they should also emit radiation at the same THz frequencies when heated based on Kirchhoff's law [28]. The emission spectra of the three samples at 400 °C were measured using the same FTIR spectrometer by directing the emitted radiation to its external port. The samples were placed on top of a hot plate covered by front-coated Al mirrors, which were found to have very low emissivity (~0.02) in the THz spectral range. These mirrors prevent unwanted thermal radiation from the uncovered portions of the hot plate from reaching the FTIR detector. A gold plated 90-degree f/1 off axis parabolic mirror, with focal length of 50 mm was used to collimate the radiation emitted by the metamaterial emitters before directing it to the external port of the FTIR. The emission spectrum of a reference emitter (a silicon wafer coated with black carbon) was used to extract the emissivity of the metamaterial samples as a function of THz frequency. The emissivity spectra, shown in Fig. 3 were obtained by dividing the sample data by the corresponding data obtained using the blackened emitter heated to the same temperature (400 °C).
Fig. 3. Measured emissivity of the metamaterial samples A, B and C at 400 °C. Emissivity exhibits peaks at 4.1, 5.4 and 7.8 THz, respectively.

4. Discussion

It is clear that the emission spectra in Fig. 3 agree well with the measured absorption data in Fig. 2 as expected from Kirchhoff's law. The emission bandwidth at half maximum for each metamaterial structure is approximately 1 THz. The total power emitted into each THz band per unit area ($P$) can be estimated by integrating Planck's blackbody radiation formula ($P(\nu)$) multiplied by the measured emissivity ($\epsilon(\nu)$) within the emission bandwidth as:

$$P(\nu) = \frac{2h}{c^2} \int \frac{\epsilon(\nu) \nu^2}{\exp\left(\frac{h\nu}{kT}\right)-1} d\nu, \tag{1}$$

where $h$ is Planck’s constant, $c$ is the speed of light in vacuum and $k$ is Boltzmann’s constant. The estimated power per unit area, based on Eq. (1), for samples A, B and C operated at 400 °C is 11, 18 and 36 W/m² respectively. For comparison, total emission from approximately 300 mm² area of metamaterial (sample C) is needed to get the average power emitted by a high power QCL operating at 4 THz, which is 5-10 mW [3, 6, 29].

In addition to probing the spectral characteristics of emissivity, dependence of emitted power with temperature was also measured. Figure 4 shows irradiance (the FTIR detector signal) spectra of sample A measured at 140, 280 and 400 °C. The peak emission remained near 4.2 THz, which indicates that thermal expansion of the metamaterial structure in this temperature range is not appreciable. However, the magnitude of the peak emission increased linearly with temperature as shown in the inset of Fig. 4. This behavior is excepted since in 1-10 THz range, Planck's law can be approximated to the Rayleigh-Jeans [30] limit ($h\nu < kT$) which is given by:

$$P(\nu) = \frac{2kT\nu^2}{c^2}. \tag{2}$$

The temperature dependence in Eq. (2) confirms that the emitted power is proportional to the temperature as observed experimentally.
The emissivity spectrum can be extended to multiple well-separated bands by designing metamaterial THz emitters with the appropriate geometry. A dual-band THz emitter was fabricated (sample D) and characterized using the same procedure employed for the other samples. Since all the samples were fabricated on the same wafer, the dielectric layer (SiO$_2$) thickness remained the same at 1.6 $\mu$m. In this case, the top layer of the dual-band metamaterial consists of two different size squares (10 and 18 $\mu$m) distributed in a tile-like arrangement as shown in the inset of Fig. 5. The measured emissivity of the sample at 400 °C multiplied by the Planck's blackbody radiation formula (excitance) at 400 °C is shown in Fig. 5. The blackbody spectrum is also plotted (dashed line) as evidence that high emissivity was achieved for both bands. The smaller squares are responsible for the higher frequency resonance at 6.8 THz and the larger squares are responsible for the lower frequency resonance at 4.0 THz.
The ability to choose the appropriate dimensions and combinations of squares in addition to the dielectric material and thickness to produce the desired response makes metamaterials an attractive option to engineer a specific THz emission profile. The enhanced THz emission from the metamaterial structures was also observed using a microbolometer infrared camera fitted with a Tsurupica lens, which ensured that only THz radiation reached the camera. Note that the camera is not optimized for THz imaging [8, 30]. Figure 6(a) shows the THz image of metamaterial structures on samples B and C, heated to 400 °C while Fig. 6(b) shows the image in the visible range taken by a standard digital camera. In the THz image it is easy to identify the metamaterial regions (brighter), the aluminum lines that separates the metamaterial structures (darker) and also the exposed SiO2 ring, which was found to have substantially higher emissivity than that of Al in the THz spectral range the camera lens transmits (see the inset in Fig. 6(c)).

Figure 6(c) shows the transmittance of Tsurupica lens along with the irradiance spectra of sample B and a uniform Al film. The data in Fig. 6(c) shows that emitted THz power from Al is much smaller than that of the metamaterial. The low emissivity of Al relative to the metamaterial structures is responsible for dark lines in the THz image. The inset in Fig. 6(c) shows the Tsurupica transmittance extended to IR range.

5. Conclusion

In summary, we have demonstrated metamaterial-based selective emitters operating with near unity peak emissivities with peaks in the 4 to 8 THz interval. The absorption characteristics
agree well with the measured emissivities showing that Kirchhoff’s law applies to metamaterials in the THz range. Furthermore, emitted THz power from the samples has a linear dependence on temperature since emission in this range can be approximated to the Rayleigh-Jeans limit. Multiband THz emission capabilities were also demonstrated using more complex unit cells in the metamaterial. Design accuracy, fabrication simplicity and high power make the metamaterial emitters very attractive for applications that seek narrow band THz sources.

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