Simulation of Thermal Processes in Metamaterial MM-to-IR Converter for MM-wave Imager

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Abstract. The main characteristics of MM-wave image detector were simulated by means of accurate numerical modelling of thermophysical processes in a metamaterial MM-to-IR converter. The converter represents a multilayer structure consisting of an ultra thin resonant metamaterial absorber and a perfect emissive layer. The absorber consists of a dielectric self-supporting film that is metallized from both sides. A micro-pattern is fabricated from one side. Resonant absorption of the MM waves induces the converter heating that yields enhancement of IR emission from the emissive layer. IR emission is detected by IR camera. In this contribution an accurate numerical model for simulation of the thermal processes in the converter structure was created by using COMSOL Multiphysics software. The simulation results are in a good agreement with experimental results that validates the model. The simulation shows that the real time operation is provided for the converter thickness less than 3 micrometers and time response can be improved by decreasing of the converter thickness. The energy conversion efficiency of MM waves into IR radiation is over 80%. The converter temperature increase is a linear function of a MM-wave radiation power within three orders of the dynamic range. The blooming effect and ways of its reducing are also discussed. The model allows us to choose the ways of converter structure optimization and improvement of image detector parameters.

1. Introduction and background

Last years the intensive researches are directed towards the development of image detectors for a millimeter-wave range of electromagnetic spectrum. This range is considered as perspective for various application such as security systems, noninvasive biomedical diagnostics, and nondestructive control of material quality. In previous works [1-4] we have proposed a MM-to-IR converter for real-time millimeter-wave imaging.

The MM-to-IR converter represents a multilayer structure (figure 1) consisting of an ultra thin resonant metamaterial absorber and a highly efficient emissive layer with a perfect emissivity factor. The absorber consists of a dielectric self-supporting film with thickness much less than the operational wavelength. Film is metallized from both sides. A micro-pattern is fabricated from one side by contact photolithography. This structure was utilized as a frequency-selective artificial impedance surface with a configuration “metasurface + grounded dielectric slab”. Resonant absorption of the MM waves induces the converter heating that yields enhancement of IR emission from the emissive layer. IR
emission is detected by a high sensitive IR camera. The proposed MM-wave imager consists of MM-to-IR converter and IR camera with noise equivalent temperature difference (NETD) 40 mK. In this scheme the main parameters of the MM imager are determined by IR camera parameters and thermal processes in the converter. In this contribution an accurate numerical model of the converter was created and thermal processes in the converter structure were simulated by using COMSOL Multiphysics™ software. The main characteristics of MM-wave image detector were estimated and were compared with experimental results.

![Figure 1. Structure of the MM-to-IR converter consisting of frequency-selective surface (FSS), dielectric film (D), "ground" layer (GL), IR emissive layer (EL).](image1)

![Figure 2. Model of the converter. PP – polypropylene, Al – aluminum, T\(_{\text{fix}}\) – fixed temperature.](image2)

The simulation was performed to determine the limiting characteristics of the MM-to-IR converter, i.e. the maximum achievable detector characteristics. For this purpose a model of the converter has been introduced (figure 2). The model is a thin membrane placed in a vacuum. Thin dielectric layer forms the body of the membrane (in this case it’s a polypropylene film). Frequency-selective surface (FSS) is given by a boundary condition of the incoming radiation power with absorption factor of 100%. The actual thickness of the aluminum FSS layer (0.4 μm) is neglected due to its low heat capacity and low thermal conductivity because of its disconnectedness. 0.4 μm aluminum ground layer is applied to the opposite side of the dielectric layer. IR emissive layer is given by a boundary condition of the thermal radiation with emissivity of 0.8 that is put on the dielectric layer surface. We neglect the actual thickness of the emission layer, as the thickness of this layer can vary depending on the technology.

2. Results

A round converter with a diameter of 50 mm was used for a simulation. The center of the converter was illuminated by Gaussian beam with a diameter of 25 mm.

The time dependences of the converter temperature, obtained from the COMSOL simulations are shown in figure 3. The simulation showed that the response time (τ) of the converter temperature under MM-wave illumination is a linear function of the converter thickness (figure 4). The real time operation is provided for the thickness of the dielectric layer less than 3 micrometers.

The simulations show that the energy conversion efficiency (MM to IR) is over 80% that provides a high sensitivity of the detector and put it in line with modern IR-detectors. The converter temperature increase is a linear function of a MM-wave radiation power within three orders of the dynamic range.
Figure 3. Temperature change ($\Delta T$) versus time ($t$) for various polypropylene (PP) thicknesses. The time dependence of the illumination power is shown by dotted line ($P$, right scale).

Blooming effect of a thermal image of the converter is caused by the lateral heat conduction along the converter. In order to investigate the blooming effect, a square converter with a side length of 24 mm and 3 $\mu$m polypropylene layer thickness was simulated. The center of the converter was illuminated by a square beam. The converters with various through-the-thickness cuts that do not break the integrity of the converter were introduced in order to reduce the blooming. The converter thermal images for various types of cuts are shown in figure 5 and figure 6.

Figure 4. Maximum of the temperature change ($\Delta T_{\text{max}}$) and the response time ($\tau$) versus the thickness of the dielectric layer ($h_{\text{pp}}$).

Figure 5. Thermal image of the converter without (a) and with cuts (b). For more details see 1 and 4 cases in figure 6. In both (a) and (b) cases the illuminated area is of identical square shape in the center.

Figure 6. Normalized temperature change of the converter ($\Delta T / \Delta T_{\text{max}}$) versus coordinate (see the gray line in figure 5). Types of cuts: 1 – no cuts, 2 – the cuts in both aluminum and polypropylene layers do not break the integrity of both layers ($1.08 \times 0.1$ mm cuts), 3 – the aluminum layer is cut into isolated squares ($0.1$ mm wide cuts) and there are no cuts in the polypropylene layer, 4 – the aluminum layer is cut into isolated squares ($0.1$ mm wide cuts) and the cuts in the polypropylene layer ($0.9 \times 0.1$ mm cuts).

A comparison of experimental measurements and COMSOL Multiphysics simulations for the uncut converter of 50 mm in diameter are shown in figure 7. The converter was illuminated by
Gaussian beam. The converter consists of 20 μm polypropylene, 0.4 μm aluminum and 23 μm emissive layers.

Figure 7. Comparison of experimental measurements and COMSOL Multiphysics simulations of an uncut converter under illumination by Gaussian beam. (a) – time dependence of converter temperature change ($\Delta T_{\text{max}}$), (b) – normalized temperature change of the converter ($\Delta T / \Delta T_{\text{max}}$) along the diameter, (c) – thermal image of the converter: experiment (top) and simulation (bottom).

3. Conclusion
The simulation showed that the response time of the converter temperature is a linear function of the converter thickness, therefore the time response can be improved by decreasing of the converter thickness. The fabrication of the appropriate cuts in the converter significantly decreases the blooming of the thermal image. The simulation results are in a good agreement with experimental results that validates the model. The model allows us to choose the ways of converter structure optimization and improvement of image detector parameters.

4. References
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