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High-performance spectrally selective pyroelectric detection of millimeter and submillimeter waves using ultra-thin metasurface absorbers

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Introduction

In the last decade, following a rapid progress in millimeter-wave (MMW) and submillimeter-wave (SMMW) technologies [1, 2], a lot of efforts are undertaken in device physics to improve conventional or realize novel instrumental solutions using metamaterials. Indeed, the metamaterial structures, especially the plasmonic ones, are capable of noticeably extending functional properties of MMW/SMMW devices hardly attainable with classical approaches. In particular, via tailoring the structure's absorptivity A it is possible to attain $A\approx100\%$ when the structure's thickness d is much smaller than the peak absorption wavelength λ [3–5]. Such a solution is highly demanded in thermal detectors, e.g. pyroelectric ones, since minimization of d is essential for decreasing the absorber's thermal capacity and, therefore, for achieving high sensitivity and low response time of the thermal device. Due to the small thickness ("ultra-thinness"), such artificially engineered planar subwavelength structures are frequently referred to as metasurface absorbers (MSAs). It is worth noting that thinning the MSA inevitably leads to narrowing its fractional absorption bandwidth $\Delta\lambda/\lambda$.This conclusion stems from the fundamental Rozanov restriction on the thickness of an arbitrary metal-backed magnetodielectric absorber [6]:

$$d \geq \left|\int_0^\infty ln|S_{11}(\lambda)|d\lambda\right|/(2\pi^2\mu_s), \qquad (1)$$

where S_{11} is the amplitude reflection coefficient and μ_s is the relative static magnetic permeability of the slab.

The narrowband response of ultra-thin MSAs is usually adduced as their drawback incompatible with broadband applications. On the other hand, the conditions $d/\lambda << 1$ and $\Delta\lambda/\lambda << 1$can be turned to the advantage as they readily allow implementation of thermal sensors with high spectral discrimination. Arranged in compact spectrometric arrays with tailored spectral and polarization responsivities, the MSA-based detectors do not necessitate the use of external dispersive elements to measure radiation spectra and polarization, as well as to realize wavelength- and polarization-sensitive imaging [5]. Such a novel instrumental solution is commercially unavailable for MMW/SMMW bands, wherein it is relevant for numerous applications.

In this contribution we overview the results of theoretical and experimental investigations of high-performance MSAs designed for narrowband operation in the frequency range of 0.1–1 THz and integrated with compact spectrometric detectors of a pyroelectric type. The detectors were developed for spectral analysis of high-power broadband subterahertz emission from a plasma source driven by a high current relativistic electron beam at the GOL-3 plasma facility (BINP SB RAS, Novosibirsk) [7].

MSA Fundamentals

In a basic design, the MSA is realized as a single-layer frequency selective surface (FSS) of a capacitive type patterned on a thin dielectric slab with uniform back metallization ("ground plane" or GP) (Fig. 1,a). In an equivalent circuit approach [8, 9] the lossy grounded slab of a small thickness ($d/\lambda \ll 1$) is described as an effective inductor with the input impedance $Z_S \cong j\omega L_S + R_{GP}$, where $L_S = \mu\eta_0 d/c_0, \mu$ is the relative magnetic permeability of the slab, $\eta_0 \cong 377\,\Omega$ is the free spaceimpedance, c_0 is the speed of light, ω is the angular cy, R_{GP} is the lumped resistance. The MSA is interpreted as a parallel connection of the impedanceZ_S and the FSS impedance $Z_{FSS} = 1/(j\omega C_{FSS}) + j\omega L_{FSS} + R_{FSS}$ (Fig. 1, b). Since $\mathrm{Im}(Z_{GP}) > 0$ and $\mathrm{Im}(Z_{FSS}) < 0$ within the MSA band, the structure acts as a resonant LCR-circuit. By properly adjusting the equivalent circuit parameters $\{C_{FSS}, L_{FSS}, R_{FSS}, R_{GP}, L_S\}$ the MSA impedance in the resonance can be settled equating to that of free space: $(Z_{FSS}^{-1} + Z_S^{-1})^{-1} = \eta_0$. Under this condition the MSA exhibits no reflection that means total absorption of the impinging wave: $A = 1 - |S_{11}|^2 = 0$.

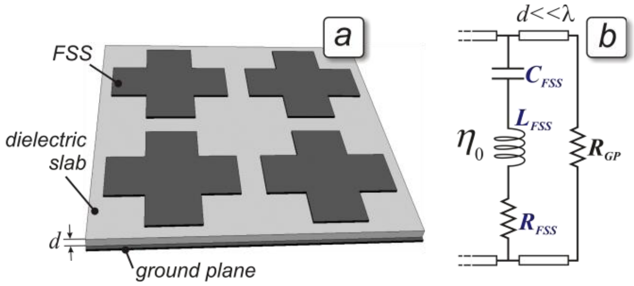

Fig. 1. (a) MSA structure by the example of FSS with cross-shaped metallic elements. (b) Equivalent circuit representation of the MSA. The resistanceR_{FSS} describes cumulative energy dissipation in the FSS and dielectric slab, while $R_{GP}$is in charge of ohmic losses in the ground plane

The fractional bandwidth $\Delta\lambda/\lambda$ and the thickness-to-wavelength ratio $d/\lambda$for the absorption resonance are compactly expressed via the resistive parameter $r = (R_{FSS} + R_{GP})/\eta_0$:

$$\Delta\lambda/\lambda \cong 4\sqrt{r}/(1+\chi), \quad d/\lambda \cong \sqrt{r}/(2\pi\mu), \qquad (2)$$

where $\chi = [1 + 4L_{FSS}/(C_{FSS}\,\eta_0^2 r)]^{-1/2}$[9]. The relations (2) distinctly necessitates the use of low-loss materials in the MSA configuration as it allows minimizing the thickness and bandwidth of a thermal sensor due to decreasing the resistive parameter$r$. In this work, polypropylene (PP) and thermally sputtered aluminium were chosen as optimal materials for the MSA implementation (see also [8, 9]).

Design and Characteristics of MSA-Integrated Pyro-Sensors

We developed a set of 29 selective with spectrally shifted sensitivities, gradually overlapping the frequency range from 94 GHz to 1 THz. Each detector was produced via combining an ultra-thin MSA with a discrete commercial IR pyro-sensor MG33 from the Russian manufacturer "Vostok" (Fig. 2, a, b) [9]. All 29 spectrally different MSAs were implemented on basis of a PP film 15 μm thick, thus yielding ratios $d/\lambda = 1/213–1/20$ at the fractional absorption bandwidth $\Delta\lambda/\lambda = 3–6\%$. The geometry of cross-shaped polarization insensitive metallic elements was chosen in the FSS design (Fig. 1, a), while their optimal structural parameters were found via 3D full-wave simulations in ANSYS Electromagnetic Suite software. The FSS micro-patternfabrication was realized with a conventional technology of contact photolithography, which was specially adapted for a work with flexible PP substrates [10].

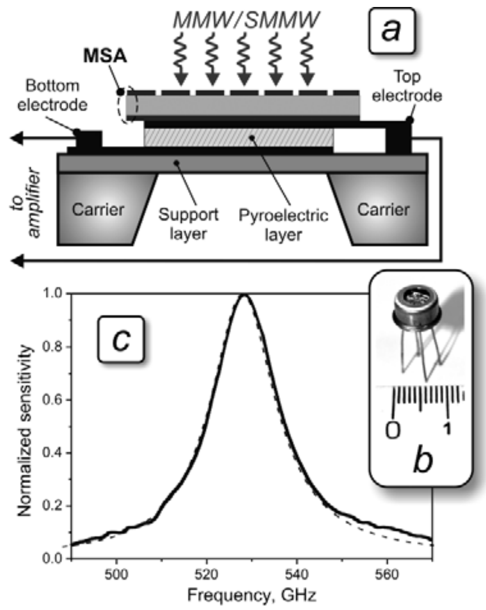

Fig. 2. (a) Sketch of the pyroelectric sensor with an integrated resonant absorber. (b) Appearance of the accomplished sensor in a standard KT-3 housing. A fragment of the ruler with 1 mm marks is shown for scale. (c) Example of spectral characteristics for the detector optimized for 530 GHz: *dashed line* – absorptivity of the free-standing MSA; *solid line* – normalized sensitivity of the MSA-integrated sensor

The basic scheme for a MSA-integrated detector is shown in Fig. 2, a. Its pyroelectric part is represented by a pyroelectric layer with top and bottom metallic electrodes, which are electrically connected with an integrated preamplifier and collect a pyroelectric charge induced in the pyro-layer. Manufactured independently, the MSA is attached directly to the top electrode through the GP layer and fixed throughout the periphery with a heat-conducting paste. Upon resonant absorption of the incoming MMW/SMMW radiation in the MSA, the induced heat is rapidly transferred to the pyroelectric and generates the wanted electric signal.

Spectral characterization of the developed MSAs and MSA-integrated sensors using the techniques of BWO-based and laser-driven CW THz spectroscopy demonstrated good concordance between simulations and measurements (Fig. 2, c). Our tests also showed that in the MMW/SMMW bands such detectors keep high values of their response speed (~2–3 ms) and sensitivity (~ 50 kV/W, NEP ~ $1.0\cdot10^{-9}$ W/Hz$^{1/2}$) changed insignificantly against the regime of IR detection. In tote, the proposed approach represents an effective and relatively low-cost instrumental solution in the technology of uncooled thermal sensors.

Acknowledgements

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