Frequency Filters and Planar Lenses for the Terahertz Band: Configurations with Low- and High-Aspect Microstructures

Sergei A. Kuznetsov1,2,3, Mikhail A. Astafev1, Alexander V. Gelfand2, Alexandr N. Gentselev3, and Victor P. Bessmeltsev4
1Novosibirsk State University, Novosibirsk, 630090 Russia
2Budker Institute of Nuclear Physics, Novosibirsk, 630090 Russia
3Institute of Semiconductor Physics SB RAS, Novosibirsk Branch “TDIAM”, Novosibirsk, 630090 Russia
4Institute of Automation and Electrometry SB RAS, 630090 Russia

Abstract—We overview the results of experimental development of high-performance frequency filtering and beam focusing devices operating at subterahertz and terahertz frequencies. The quasi-optical band-pass and high-pass filters, as well as planar lenses implemented as subwavelength metallized microstructures with thickness both of the order and much smaller than the wavelength are described. The techniques for fabricating these low- and high-aspect structures using lithographic and laser micromachining technologies are considered.

I. INTRODUCTION

Compared to visible and near infrared ranges of the electromagnetic spectrum with their high diversity of available optical components, the relatively young terahertz (THz) band occasionally faces the lack of high-performance devices demanded in experiments on specific spectral filtering and radiation focusing. At the same time, the THz range is proven to be technologically convenient for implementing spectrally-selective quasi-optical components based on metallized microstructures (MMSs) of sub-wavelength topology, which are capable of effectively solving the aforementioned task. Introduced in microwave antenna engineering as frequency selective surfaces [1], MMSs allow one to properly manipulate amplitude, phase and polarization response of the structures through an appropriate choice of their topological pattern and a number of layers used, while their patterning can be relatively easily realized via well-tailored lithographic or laser micromachining techniques of micrometer accuracy [2-5]. Among MMSs of keen interest augmented last years, the structures with a properly designed spatial-dependent transmission/reflection phase should be highlighted [6]. Such MMSs make feasible purely flat, thin and light-weight THz focusing devices, which serve as the attractive alternative to the conventional diffractive optical elements based on cost-consuming metallic or semiconductor structures with profiled surfaces [7, 8].

In this contribution we present recent results of developing high-performance single- and multi-layered MMSs optimized for frequency filtering and focusing applications in the THz band. In particular, this work extends our R&D activity, previously limited by considering MMSs with metallization thickness t much smaller than the operating wavelength λ (so-called “low-aspect” structures or LA-MMSs) [3-6], to MMSs with $t \ll \lambda$. The latter ones have lateral dimensions typically much smaller than $t$ and are referred to as the “high-aspect” (HA-MMSs). Produced with deep X-ray lithography, the properly designed HA-MMSs exhibit extra functionalities, e.g., enable efficient high-pass filtering or transmit-array lensing using only a single-layered configuration.

In toto, we discuss electromagnetic features and present the results of experimental implementation for the following devices:

a) an extended set of multi-layered LA-MMSs-based band-pass filters with peak frequencies positioned within 0.1-3 THz;

b) single- and bi-layered LA-MMS-based reflect-array lenses optimized for 0.35 and 0.65 THz;

c) single-layered HA-MMS-based high-pass filters optimized for sharp cut-off below 0.3 and 0.5 THz;

d) single-layered HA-MMS-based transmit-array lenses optimized for 0.65 THz.

II. SELECTED RESULTS

A. Band-Pass Filters

We developed a series of quasi-optical band-pass filters originally designed for integration with multi-channel radiometric systems at the GOL-3 nuclear fusion facility [4] to measure spectra of THz emission from turbulent plasma within the frequency range from 0.1 to 3 THz (Fig.1.a). The filters are implemented as multilayer resonant structures of the multiplex (non-interference) type and utilize substrate-free copper LA-MMSs produced via electroplating. Having the typical relative bandwidth around 15–20 %, the filters exhibit the high peak transmittance (88–97 %) and low out-of-band spectral leakage evaluated at the level of –30–45 dB.

B. High-Pass Filters and Transmit-Array Lenses

The LIGA technology is a well-known technique based on deep X-ray lithography to fabricate HA-MMSs [9]. In this work, a set of LIGA structures designed as high-pass filters and planar transmit-array lenses were produced and experimentally investigated at the Siberian Synchrotron and Terahertz Radiation Center (SSTRC, Novosibirsk, Russia). The structures were fabricated from PMMA slabs 1 mm thick via their exposing to hard X-ray radiation through X-ray masks produced in advance by laser micromachining of brass foils. The entire surface of the patterned PMMA substrates was metallized afterwards through deposition of silver 1 um thick. This patented method [10] was utilized to manufacture HA-MMSs with hexagonally-shaped through holes having the minimal value of the inter-hole cross-arm width around 65 um (Fig.1.c). In high-pass filters (Fig.1.b) the hole’s dimensions were fixed, while in transmit-array lenses (Fig.1.d) a specific surface variation of the hole diameter was introduced to...
change properly the local value of the effective refractive index necessary for focusing. For the developed LIGA-lenses their diffraction efficiency was estimated to be around 70% at the operational bandwidth of 10%.

C. Reflect-Array Structures

In a conventional design the reflect-array structure implies a grounded-dielectric-slab-backed LA-MMS with a spatially-dependent reflection phase which is achieved via proper changing the MMS unit cell geometry. The Fig.2.a represents one of the possible routes for topological morphing to cover the range of 360° phase variation, which was realized in this work to implement the reflect-arrays operating at 0.35 THz under 45° oblique incidence. The morphing was realized through continuous transformation of square-shaped metallic patches to U-shaped resonators (USRs) and then to split-ring resonator elements (SRRs) excited by the TE-wave polarized transversely to USR and SRR slots [6]. Patterned on polypropylene substrates with the thickness of 190 µm, the reflect-arrays were designed to have the unit cells periodicity close to λ/3. By applying a computer holography technique to synthesize an optimal surface phase distribution, both simple (“1 spot”) and sophisticated reflective focusing (“4 spots”) with the diffraction efficiency reaching 80% was successfully demonstrated in this work (Fig.2.b).

Fig. 1. (a, b) Examples of the experimentally measured transmittance for 6 band-pass and 1 high-pass filters. (c, d) Micro- and macroscopic photographs of the HA-MMS-based transmit-array lens. On the upper graphs the numbers indicate the peak transmission frequencies given in THz.

Fig. 2. “Patch-to-SRR” topological morphing (a) employed in holographic reflect-arrays to attain highly-efficient single and multi-spot focusing at 0.35 THz (b). The geometric parameters are given in micrometers.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Education and Science of the Russian Federation under the State Assignment Contract #3002 (technological implementation and experimental testing) and the Russian Science Foundation under the Project 14-12-01037 (full-wave EM simulations).

REFERENCES