DEVELOPMENT OF METAL MESH BASED QUASI-OPTICAL SELECTIVE COMPONENTS AND THEIR APPLICATION IN HIGH-POWER EXPERIMENTS AT NOVOSIBIRSK TERAHERTZ FEL*

S.A. Kuznetsov#, BINP SB RAS, Novosibirsk State University,
Novosibirsk, 630090, Russian Federation
V.V. Kubarev, P.V. Kalinin, B.G. Goldenberg, V.S. Eliseev, E.V. Petrova, N.A.Vinokurov
BINP SB RAS, Novosibirsk, 630090, Russian Federation

Abstract

In this paper we discuss main types of metal mesh based passive selective components of THz-quasi-optics required for applications in experiments at Novosibirsk terahertz free electron laser. The first experimental results on development of thin-film metal mesh polarizing beamsplitters and frequency filters by methods of photolithography and electroforming are presented. The technological aspects of the promising LIGA-technique being in progress in the Siberian synchrotron radiation centre and destined for production of thick metal mesh components with thickness compared to radiation wavelength are described.

INTRODUCTION

Successful realization of scientific programs of the Siberian Centre of Photochemical Research [1, 2] operating on basis of Novosibisk terahertz free electron laser (NovoFEL), which fundamental generation harmonics overlaps a spectral range 1.3÷2.5 THz, requires application in user experiments different types of passive quasi-optical selective devices intended for spatial and frequency gating of powerful beams of NovoFEL radiation. The necessary instrumentation includes beam-splitters, attenuators, frequency filters and some elements of focusing optics. Along with desired selective characteristics such devices should be capable of operating over a long period of time under high-power load conditions without noticeable degradation of their properties. It admits to employ in selective components only low absorbing and thermostable materials, such as high conductivity metals and special types of polymers. The best solution is in use of metal mesh structures with specially designed subwavelength topology of mesh cells. For minimizing absorption the metal structures should be wafer-free, however in case of non-self-bearing topology or small metallization thickness structure fastness requires presence of supporting thin-film polymeric substrates.

In this report we discuss selective properties of the main types of metal mesh structures required for NovoFEL experiments and present first results of development of metal mesh components by three different manufacturing techniques: a) contact photolithography; b) electroforming; c) LIGA. Dealing with a minimal topological size of the mesh pattern about a few microns, each of these techniques enables to produce mesh components within its own corresponding range of metallization thickness: a) ≤1 μ; b) ~10 μ; c) ~100 μ.

It should be elucidated that conventional photolithography is considered to be the most adequate, relatively cheap and well-proven technology for manufacturing metal mesh quasi-optical components traditionally used in low- and moderate-power THz-applications. In NovoFEL user experiments employment of such "photolithographic" components is restricted due to high average power of NovoFEL radiation, reaching 400 W nowadays and expected to be raised in the future. Small thickness of metallization and presence of dielectric carrier substrates in such components limit their surface and volumetric thermal conductivity resulting in danger of quick overheating and destruction under high-power load conditions. The best "high-power" alternative to "photolithographic" components (in case of self-bearing topology) are the components based on substrate-free self-supporting thick metal mesh structures manufactured by conventional electroforming and LIGA techniques. In spite of higher technological costs such components are of great interest for NovoFEL applications since they are much more thermostable and mechanically firm and have a much higher radiation destruction threshold. Another inherent and important feature of thick metal structures is much stronger low-frequency attenuation due to a waveguide cut-off effect that can be effectively used for solving problems of harmonics filtration and THz-beams intensity control discussed below.

THZ-COMPONENTS REQUIRED FOR NOVOFEL APPLICATIONS

By fundamental practical purpose influencing on choice of mesh pattern topology the metal mesh based selective components should be divided into three main groups (see Fig.1): 1) beam-splitters (attenuators); 2) frequency harmonics filters; 3) diffractive optical elements.

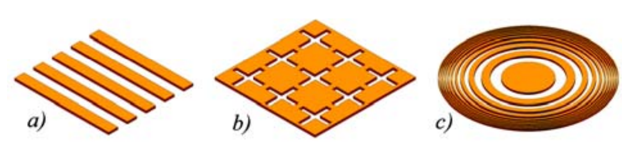

Figure 1: Fundamental types of metal mesh based components required for NovoFEL experiments: *a*) polarizing beam-splitter; *b*) frequency filter; *c*) diffractive optical element (amplitude transparency).

* This work is supported in part by the Russian Foundation for Basic Research (project No. 07-02-01459-a).
# sakuzn@inp.nsk.su

Wideband beam-splitters and attenuators

Urgency of these components is connected with necessity of NovoFEL radiation distribution over simultaneously operating different user stations, as well as THz-beams multiplexing and beam intensity control in various user experiments. Due to almost 100% polarization linearity of FEL's radiation [3] the best solution is in use of polarizing grids or 1-D meshes (Fig. 1a) with a grid pitch g much less than operating wavelength λ. Such grids reflect effectively the E-polarized component of the incident radiation and transmit its H-polarized component that enables to control intensity of transmitted or reflected radiation by choosing an appropriate orientation angle of the grid. For simultaneous operation of different user stations the NovoFEL facility needs beam-splitters with clear aperture diameter up to ~250 mm at minimally realized grid pitch values.

It should be pointed out that for a fixed value of $min(g)$, which is determined by technological limitations, operational efficiency of a polarizing beam-splitter can be greatly enhanced by increasing its metallization thickness t. As t grows the grid slots begin to manifest waveguide properties that results in exponential decrease of the spectral transmittance for the E-polarized incident wave due to a waveguide cut-off effect (Fig. 2a). For H-polarization there is no prohibition on waveguide mode propagation but in contrast to the case $t \to 0$ the transmittance appears to be frequency modulated (Fig. 2b). The last effect is explained by excitation of standing waves inside waveguide slots due to partial reflection of the propagating wave from the input and output slot boundaries. The approximate spectral positions of H-transmission minima and maxima can be obtained from the formulas of Fabry-Perot resonances:

$$\lambda_{\min} \approx 2t/(m+1/2)\,,\ \lambda_{\max} \approx 2t/m\,,\ m \in \mathrm{N}\,.$$

In practice, for eliminating the negative effect of H-transmission modulation it is recommended to mount a polarizing beam-splitter at the angle of incidence $\varphi = \arccos(q)$, where q is relative width of grid slots. In this case reflection of the H-polarized wave vanishes due to Malyuzhinets effect.

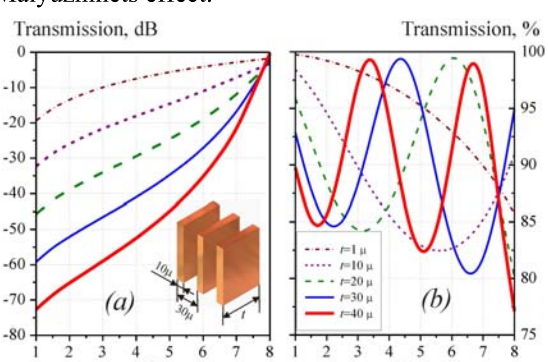

Figure 2: Numerical simulation of influence of metallization thickness t on frequency response of a copper polarizing beam-splitter (normal incidence): *a*) E-polarization (**E** || slots); *b*) H-polarization (**H** || slots).

Harmonics filters

Detailed spectral measurements of NovoFEL radiation show that along with a fundamental generation harmonics (λ = 118–235 μ) the laser spectrum contains the second and the third ones which relative power in optimized regimes reaches relatively high values: 2 % and 0.6 % respectively [4]. A study of these short-wave spectral components and their interaction with investigated samples is a subject of great interest.

For filtering the higher FEL's harmonics at simultaneous strong (≥40 dB) suppression of the 1st one the following 2-D metal mesh structures can be applied:

– Nonresonat "inductive" meshes with circular openings (Fig. 3a, 6). At thickness t compared to radiation wavelength such meshes act as effective high-pass filters, which efficiency of low-frequency attenuation below the point $\nu_{\text{cutt-off}} \approx 1.841 \cdot c/(\pi d)$ is enhanced by the factor ~$32 \cdot t/d$ (dB) in comparison with similar thin meshes due to a waveguide cut-off effect.

– Resonant "inductive" meshes of crossed dipole slots (Fig. 3b, 5b) with resonant band-pass transmission at wavelength close to doubled slot length L. For small metallization thickness (t~1 μ) such single meshes provide not higher than ~20 dB out-of-band attenuation. It can be augmented at low frequencies by increasing t.

– Resonant "capacitive" meshes. Such meshes comprised by disjointed resonant conducting elements are effective for rejecting undesirable spectrum frequencies. Meshes with hexagonally packed ring elements (Fig. 4) are recommended for proving a widest rejection band (FWHM~100%) at the maximal theoretical attenuation level ~35-40 dB.

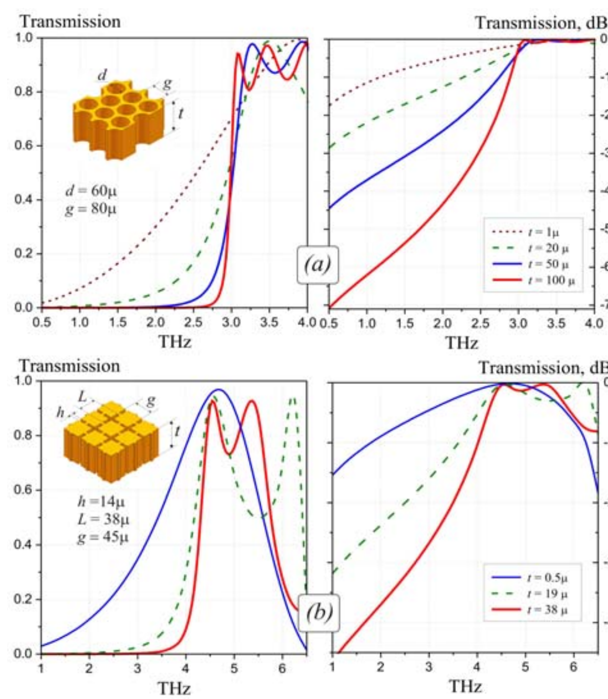

Figure 3: Frequency response of nonresonant high-pass (a) and resonant band-pass (b) copper single-layer mesh filters for different metallization thickness t.

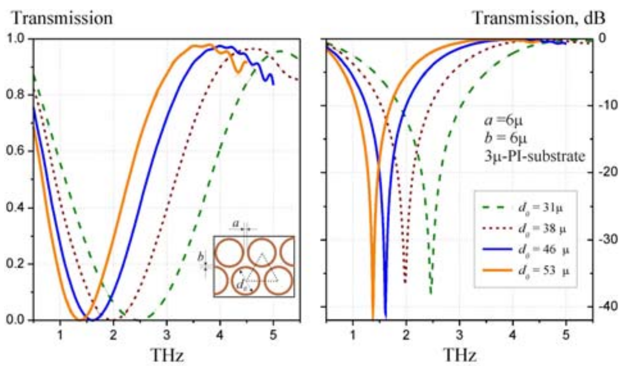

Figure 4: Simulated band-stop properties of thin single resonant meshes with hexagonally packed circular ring elements (*t*~0.45μ, *Al*) deposited on a 3μ-polyimide film.

Diffractive optical elements (DOEs)

DOEs (Fig. 1c), conditionally called as "irregular 2-D mesh structures", are intended for focusing THz-radiation into a spot of a desirable shape. Such a problem arises for instance in scheduled THz-experiments on governing supersonic gas flows by controlling radiation energy deposition inside a specified volume [5]. In contrast to "non-diffractive" mesh structures considered above DOEs operate in a high order diffraction mode that is provided by the greater topological size of a "mesh" pattern ($g > 2\lambda$). Detailed consideration of DOEs is beyond the scope of our paper and can be found for instance in [6].

SAMPLE THZ-COMPONENTS PRODUCED BY PHOTOLITOGRAPHY AND ELECTROFORMING

In the framework of the THz-instrumentation development task we have adapted and successfully tested the technology of contact micro-photolithography for manufacturing thin-film free standing terahertz polarizers (Fig. 1a) and resonant band-pass filters (Fig. 1b) at minimal topological size of the mesh pattern 4–6 μ and clear aperture diameter ∅ 66 mm. The polyimide films 3.5 μ thick were used as bearing substrates for *Al*-mesh structures with metallization thickness 0.45 μ. The typical FIR transmission spectra of manufactured samples obtained at the "Bruker IFS 66v/s" Fourier-transform spectrometer are presented in Fig. 5. Since a radiation source used in the FT-spectrometer is originally nonpolarized an auxiliary polarizer was used for obtaining a reference signal during FIR characterization of 4x8μ-polarizers. The manufactured samples were also tested in 50 W THz-beams of NovoFEL radiation that let us measure directly transmittances of mesh samples in a low-transmission region without using a cryogenic technique. E.g. the transmittance of 4x8μ-polarizers for E-polarization appeared to be ~$3.2 \cdot 10^{-3}$ at λ = 126 μ.

The choice of thin polyimide substrates is conditioned by their satisfactory optical characteristics, high

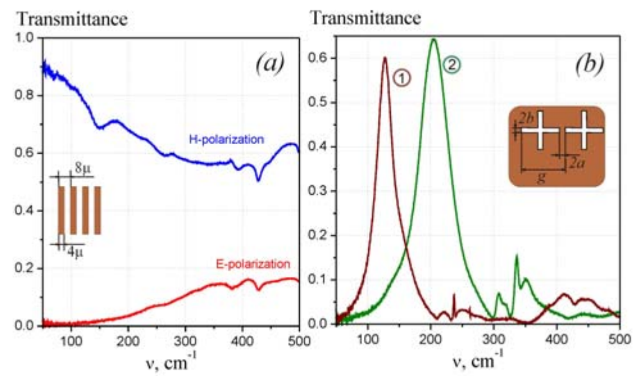

Figure 5: Spectral transmittance of experimental samples of 0.45μ-*Al*-mesh structures deposited on 3.5μ-PI-films: 1) g=41.4μ, 2a=12μ, 2b=6μ; 2) g=28.5μ, 2a=10μ, 2b=5μ.

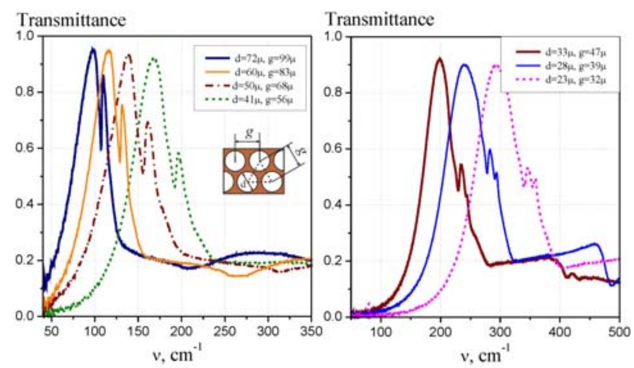

Figure 6: High-pass properties of free standing substrate-free nonresonant 9μ-*Ni*-meshes with hexagonally packed circular openings.

mechanical fastness and thermostability enabling to withstand radiation heating up to 350^{0}C. By now polyimide-film based mesh structures were successfully tested at radiation power flows ~2 kW/cm^2.

Successive use of photolithographic and electroforming techniques enables to increase mesh metallization thickness resulting in elimination of supporting polymeric substrate in case of self-bearing structures. We successfully tested this technology for production a set of dichroic high-pass filters based on electroformed *Ni*-meshes 8÷10 μ thick (Fig. 6). As such thickness is close to the upper technological limit the only alternative for its further increase is use of the LIGA-technique.

PRODUCTION OF THICK THZ-COMPONENTS BY LIGA-TECHNIQUE

In comparison with conventional photolithography the LIGA-technique being developed at the Siberian Synchrotron Radiation Centre (BINP SB RAS) is based on deep X-ray lithography and destined for producing microstructures in a wide range of their thicknesses: from a few units up to hundreds microns [7, 8]. Such an advantage of the LIGA-technology over optical and UV techniques is realized due to high penetrability of X-ray radiation into X-ray-sensitive resists and negligible effects of parasitic Fresnel diffraction that makes LIGA to

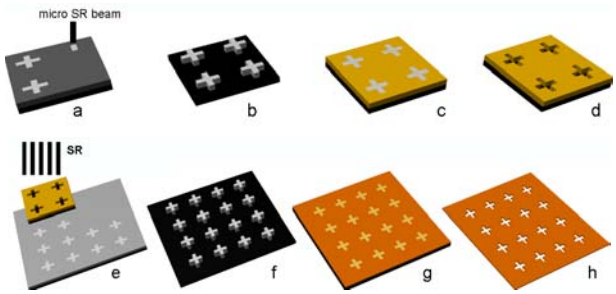

Figure 6: Main stages of the LIGA-technique: a-d) X-mask production; e-h) X-mask application for obtaining a thick metal mesh structure.

be ideal for manufacturing thick metal mesh based THz-components with extremely high aspect ratios unachievable by any other methods.

The principal stages of LIGA include production of an X-ray contrast mask which topological pattern replicates the pattern of a desired mesh structure, deep X-ray lithography via the prepared X-mask and subsequent growing of an output thick mesh structure by electroforming. At present, we master the LIGA-technique for producing self-bearing copper 2-D mesh filters 50÷100 μ thick at the minimal topological size of mesh pattern about 10 μ. The main steps of the used technology are shown in Fig. 6.

We use a direct method of X-mask creation [8] based on direct forming a latent image of the required microstructure or its fragment in the 30 μ-layer of the X-ray sensitive negative resist SU-8 deposited onto roentgenoparent wafer by irradiation under a collimated microbeam of synchrotron radiation (SR) with photon energy 4÷30 keV (Fig 6a). SR provides uniform irradiation of the SU-8 layer over its depth that result in verticality of walls in output microstructures. As roentgenoparent wafers the polished plates of special carbonic glass 500÷600 μ thick are used. After removal of the unirradiated resist by wet etching technique (Fig 6b) a thin 1÷3 μ copper sublayer and a subsequent 10÷20 μ layer of rhenium or gold are deposited onto the wafer by electroforming (Fig 6c). The layer of rhenium (gold) acts as a roentgenopaque material required for the X-mask, whereas a copper sublayer provides better adhesion of Re (Au) to the wafer surface. After final removal of the residual resist (Fig 6d) the finished X-mask with typical operating area 10x10 mm^2 is ready for next applications.

The stage of production of the output metal mesh structure (Fig 6e-h) includes steps similar to the considered above. X-ray exposure of a thick SU-8 resist deposited onto a carbonic glass wafer is realized via the prepared X-mask with subsequent multiplication of the X-mask pattern over desired area (Fig 6e). Irradiated regions of SU-8 material cross-linked after exposure and cleaned from unirradiated resist (Fig 6f) form the mask with deep vertical walls which is used for the following electroforming of a thick metal structure (Fig 6g). The maximal metallization thickness of the output mesh structure corresponds to the thickness of the SU-8 resist which is 50÷100 μ thick in our LIGA-experiments. The main problem appearing at the final step of production is separation of a copper structure from the carbonic glass wafer after removing the residual resist by wet etching (Fig 6h). This problem is solved by galvanic deposition of an auxiliary 1μ-Re-layer onto the carbonic glass wafer before electroplating of copper. It leads to decreasing copper adhesion due to passivation of Re-surface.

CONCLUSION

Rapid progress in terahertz researches connected with appearance of high-power FELs requires detailed development, designing and optimization of selective components of terahertz quasi-optics necessary for high-power applications. For future experiments at NovoFEL user stations the THz-components produced by conventional thin-film based photolithography and electroforming are considered as supplementary to thick LIGA-components which are of primary importance. We place the emphasis on development of the LIGA-technique and expect to obtain first high-quality THz-LIGA-structures in 2007-2008.

REFERENCES

[1] V. P. Bolotin, N. A. Vinokurov, D. A. Kayran et al., “Status of the Novosibirsk terahertz FEL”, Nuclear Instrum. Methods, vol. A543, pp. 81-84, 2005.

[2] N. A. Vinokurov et al., “Status of Novosibirsk ERL and FEL”, in these Proceedings.

[3] V. P. Bolotin, V. S. Cherkassky, E. N. Chesnokov et al., “Novosibirsk terahertz free electron laser: status and survey of experimental results”, Proc. Joint IRMMW-THz-2005 Conf., Williamsburg, USA, 2005, p. 495.

[4] V. V. Kubarev, N. A. Vinokurov, V. V. Kotenkov et al., “Harmonic Generation in the Novosibirsk Terahertz FEL”, in Proc. Joint IRMMW-THz-2006 Conf., Shanghai, China, 2006, p. 162.

[5] V. V. Yakovlev, V. M Fomin. “Possibilities of laser radiation application for solving aerodynamic problems”, in Proc. 1st Russian THz-Workshop “Generation and application of terahertz radiation”, 24-25 Nov., 2005, Ed. B.A. Knyazev, Novosibirsk, Russia, pp. 123.

[6] I. A. Polskikh, A. Fanova, B. A. Knyazev et al, “Diffraction Optical Elements and Optical Systems with High Power Monochromatic Terahertz Source”, in these Proceedings.

[7] W. Ehrfeld and H.Lehr. "Deep X-ray lithography for the production of three dimensional microstructures from metals, polymers and ceramics". Radiat. Phys. Chem., vol. 45, No. 3, pp. 349-365, 1995.

[8] E.V. Petrova, B.G. Goldenberg, V.I. Kondratiev et al., “Production of thick wafer based X-masks for deep X-ray lithography”, J. Surface Investigation. X-Ray, Synchrotron and Neutron Tech., 2007 (in press).