LOSSES IN OPTICAL RESONATOR OF NOVOSIBIRSK TERAHERTZ FEL: THEORY AND EXPERIMENT

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Abstract

A direct comparison of the simple universal analytical theory used earlier to design an optical resonator for the Novosibirsk terahertz free electron laser (NovoFEL) and numerous subsequent experiments is presented. A good agreement of the theory with the experiments is shown. A possibility of future optimization of the optical resonator is described.

INRODUCTION

Round trip losses are the main parameter of most laser resonators. There are many different numerical methods to calculate losses of resonators with given geometries. However, an optimal geometry is not known when a new resonator is being created. A simple search for different geometries is ineffective. In this case we need some analytical theory. In [1], the author of this paper proposed a simple universal analytical method to calculate small losses in stable open laser resonators. A comparison of the method with well-known papers in which numerical [2, 3] and cumbersome analytical [4] methods were used only for certain types of losses and geometries shows a good agreement.

On the other hand, the free electron laser gives us a unique possibility of direct experimental measurement of such losses, which is practically impossible in conventional lasers due to the inertia of their active media. First measurements of this type on NovoFEL with the start optical resonator were published in [5]; they shown a good agreement of the theory and experiment. In this paper, a nominal optical resonator with larger output coupling was investigated in a wider spectral range.

THEORY

Diffraction losses c_i caused by different small perturbations at the center of a Gaussian mode (openings) and at its periphery (mirror apertures, diaphragms, scrapers) are equal, according to [1], to double "geometrical" losses $c_i = 1 - (1 - c_g)^2 \approx 2c_g$. Geometrical losses c_g are a part of the mode cross-section overlapped (cut) by a perturbation. The total resonator losses can be evaluated as:

$$c_\Sigma = 1 - \prod_i (1 - c_i) \approx \sum_i c_i \qquad (1)$$

This property of additivity for losses at the openings and outer apertures of mirrors is shown in paper [1]. For one-type aperture losses at the periphery of a beam (mirrors, diaphragms, scrapers), the additivity condition is satisfied if the elements with losses are divided by a distance exceeding the length $L_a = d\cdot\delta/\lambda$, where d and δ are typical sizes of the mode and perturbation, and λ is the wavelength. The mode fills the cutoff part of its periphery at this distance. This condition is satisfied for the main components of our resonator losses. The losses in other sections of the resonator can be ignored because of the exponential sensitivity of the Gaussian beam to narrower diaphragms.

The calculation model of our optical resonator after some optimization of diaphragm diameters and their positions is shown in Fig.1. Values of the diameters and axial distances between the resonator center and the diaphragms are presented in Table 1. We assume that the diaphragms are full absorbing because many of them have a special absorbing ceramic coating [5] and the cross-section of vacuum pipes of our resonator is sufficiently large.

Thus, the resonator losses per round trip (for removed scrapers and symmetrical positions of all diaphragms to the resonator center) are:

$$c_\Sigma = 1 - (1 - c_{mo})^2 (1 - c_{md})^4 (1 - c_{mh1})^2 (1 - c_{mh2})^2 \times \\ \times (1 - c_{d1})^8 (1 - c_{d2})^8 (1 - c_{d3})^8, \qquad (2)$$

where c_{mo} and c_{md} are the ohmic and outer aperture losses of mirrors; c_{mh1} and c_{mh2} are the losses on openings in the mirrors; c_{d1}, c_{d2} and c_{d3} are diaphragm losses (pick-up sensor aperture, banding magnet camera aperture, and undulator aperture, respectively). For simplicity, we use one-index numeration of the losses in Fig.1, Table 1, and Fig.6, according to equations (1) and (2).

From the well-known experimental data for optical properties of solid gold, we can obtain the ohmic losses of our mirrors with gold coating: $c_{mo} = 10^{-2}(0.71\text{-}1.2\lambda$ [mm] $)$.

For losses of the Gaussian TEM_{00} - mode with the radial field distribution $E \sim exp(-r^2/r_0^2)$; $r_0 = \{\lambda L_f/\pi\, [1+ (z/L_f\,)^2]\}^{1/2}$, where L_f is the Rayleigh length, one can obtain the following formulas:

$$c_{dk,md} = exp\{-\pi d_k^2 L_f/[2\lambda(L_f^2 + z_{dk,md}^{\ 2})]\} \qquad (3)$$

$$c_{mh} = \pi d_{mh}^2/\{2\lambda L_f[1+(L_0/2L_f)^2]\}, \qquad (4)$$

where $k = 1, 2, 3$; d is the diameter of the losses component, and L_0 = 26.589 m is the resonator length.

The dependences of total losses as functions of wavelength for different Rayleigh lengths are shown in Fig.2. The value L_f = 5 m and mirror radiuses $R = L_0[1+(2L_f/L_0)^2]/2$ = 15 m were chosen as optimal in the wavelength range from 100 to 300 µm. Different losses components for this Rayleigh length are shown in Fig.6.

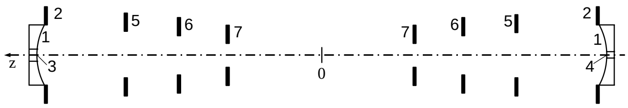

Figure 1: Calculation model of the optical resonator. Numbers at elements are *i* indexes according to equations (1) and (2).

Table 1: Diameters and positions of losses elements

Index *i*	**Diameter *d* [mm]**	**Position *z* [mm]**
2	190	13294.5
3	9	13294.5
4	3.5	13294.5
5	105	7500
6	101	6300
7	78	4500

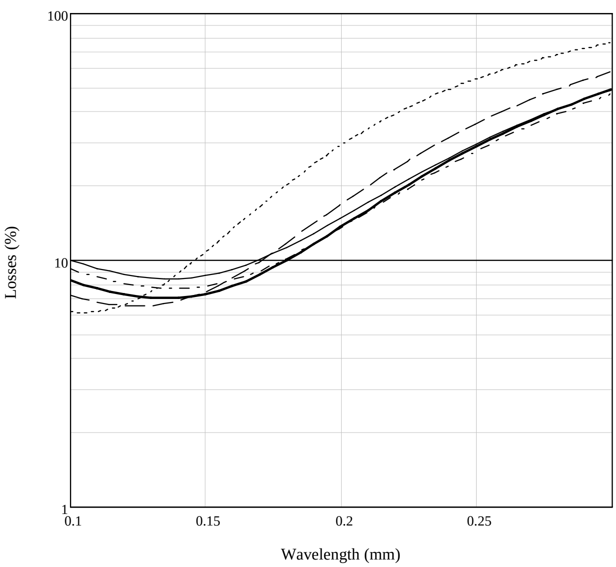

Figure 2: Total losses per round trip of NovoFEL versus wavelength for different Rayleigh lengths: L_f = 3 m (dotted line), L_f = 4 m (dashed line), L_f = 5 m (thick solid line), L_f = 6 m (dash-dotted line), L_f = 7 m (thin solid line).

EXPERIMENT

As before [5], we used in the experiments a detector on the basis of the Schottky diode matrix with a traveling wave antenna in the corner cube reflector [6]. We specially used a not the fastest Schottky detector to have a sufficient number of measured points on one light pulse. Though we checked many times the detector linearity in the measurement of CW submillimeter power, we also investigated the parameter for pulsed measurement. It is easy to see in Fig.3 that our detector is also linear in this case.

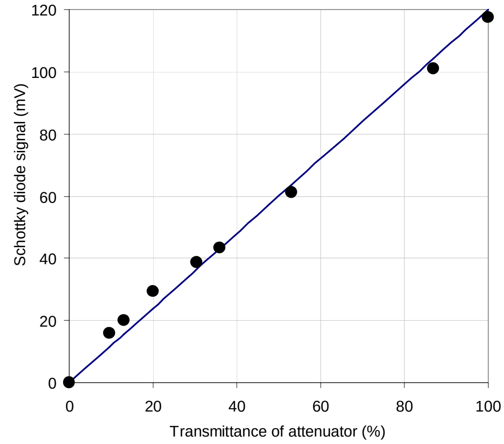

Figure 3: Signal of the Schottky diode detector versus transmission of the attenuator for working conditions of the detector.

We measured the losses of the nominal optical resonator just after its assemblage (in 2004) and recently (in June 2007) for a wider spectral range. The last experiment is shown in Fig. 4. Electron pulses of NovoFEL were switched off at the time marked by arrows. After this time, light pulses decayed exponentially for the wavelength range from 120 to 200 µm. The losses were calculated as c = 1 – T/τ, where T = 177.4 ns is the repetition period of pulses, τ is the decay time of the best exponential asymptotic. When the losses constituted about twenty percent, we did not find an exponential power decay. The losses for different periods averaged over four oscillograms are shown in Fig.5. In this case, we assume that the losses of the first decay period are more close to real losses of the NovoFEL optical resonator in the stationary regime. Thus, it is this value that is used in a comparison with the theory in the next section.

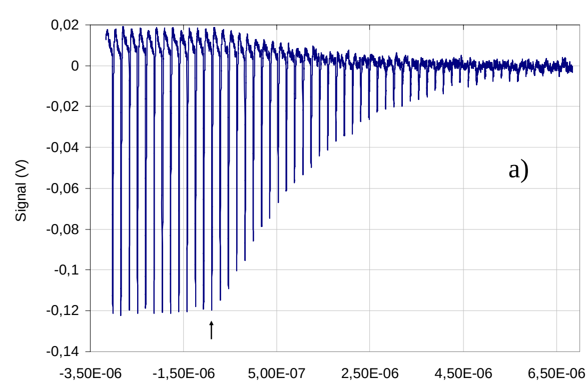

Figure 4: Time evolution of NovoFEL light pulses after switch-off of electron pulses for radiation at a wavelengths 129.8 µm (a). Switch-off time is shown by arrows.

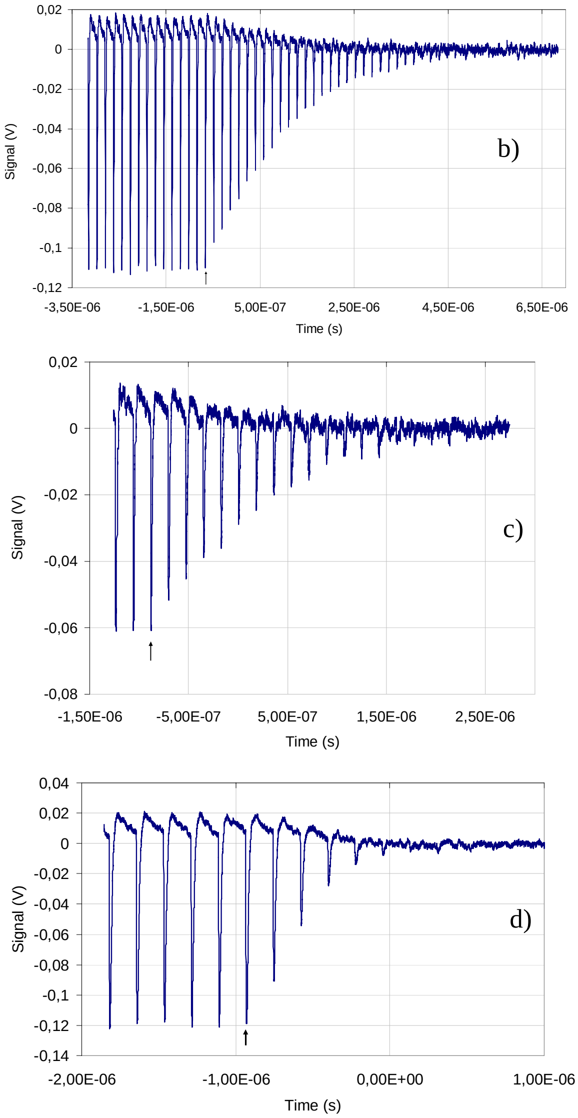

Figure 4: Time evolution of NovoFEL light pulses after switch-off of electron pulses for radiation with different wavelengths: 152.5 μm (b), 197.3 μm (c), and 229.4 μm (d). Switch-off time is shown by arrows.

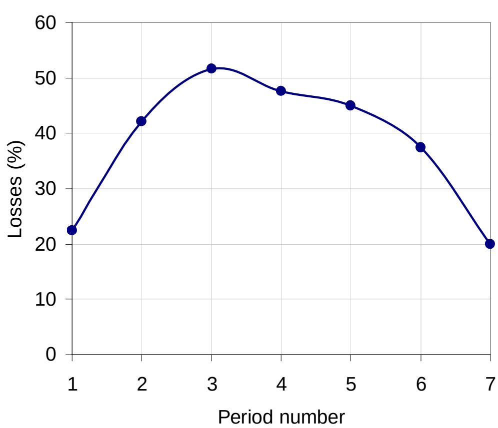

Figure 5: Losses averaged over four oscillograms versus the number of periods after switch-off for λ = 229.4 μm.

COMPARISON OF THE THEORY AND THE EXPERIMENT

A comparison of the theory and the experiment is presented in Fig.6. Different lines in the figure show various components of losses and total round trip losses according to the scheme of Fig.1 and expressions (1)-(4). We can see that the main components of losses for short wavelengths are hole losses whereas in the long wavelengths range these are diaphragm losses. Two sets of experimental points were measured in 2004 and 2007. We can see that there is a good agreement of the theory and the experiment within the accuracy of the calculation and measurement (≈ 10 %).

Nevertheless, we can assume that experimental losses somewhat exceed theoretical values. A first probable explanation of this can be some depreciation of theoretical ohmic losses in the mirrors, especially in the short-wavelengths range. These losses were calculated for an ideal optical solid gold surface. The real surface of our mirrors is a diamond machined copper surface of optical quality with a gold coating.

Most out-of-order experimental point for λ =152.5 μm was measured in regime with modulation sideband instability, which probably has a small influence on the mode intensity distribution. We plan to repeat the experiment with damped sideband instability.

Another possible correction of the long-wavelengths losses is connected with inexact axial position of the absorption diaphragms (Fig.1). Geodetic measurements give such transversal displacements of the diaphragms, which increase the total losses for λ = 200 μm by 1 %.

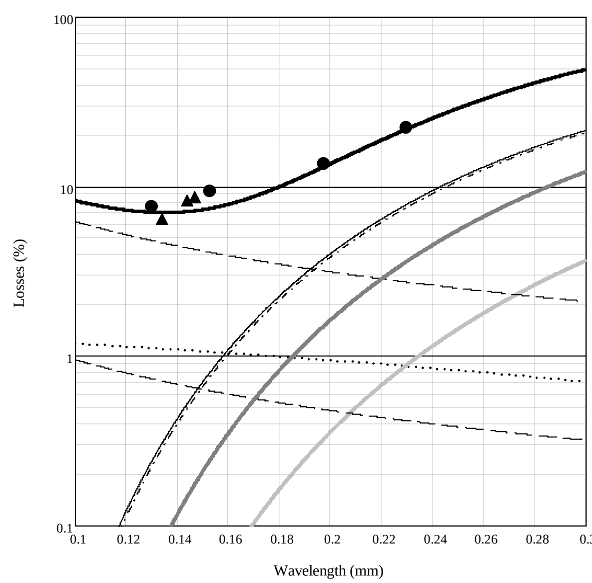

Figure 6: Theoretical (curves) and experimental (points) losses of nominal NovoFEL resonator. Theoretical curves fit the following notation in Fig.1: dotted line (1), dashed lines (3, 4), light gray line (2), gray line (6), dash-dotted line (5), and thin solid line (7); thick solid line is total round trip losses. Experimental points: circles (2007 experiment), triangles (2004experiment).

PROBABLE OPTIMIZATION OF THE OPTICAL RESONATOR

A probable optimization of the optical resonator is in increasing of the useful part of optical resonator losses, which is output power of NovoFEL. Now the power is output through circular openings at the centers of mirrors. According to the presented theory, additional diffraction losses at the openings are equal to useful losses. Thus, if we use some uniform output coupling system not perturbing the mode intensity distribution, the NovoFEL output power can be increased at least two times. A Michelson interferometer with a CVD-diamond film beam-splitter can be such a system. If the beam-splitter thickness is 53 µm and the electric field vector of laser radiation is perpendicular to the incident plane of the beam-splitter, it can overlap optimally the entire operating NovoFEL range. An additional possibility of the system is tuning of optimal output coupling for different regimes and wavelengths. The maximal value of output coupling as a function of wavelength is shown in Fig.7. The output coupling can be tuned from zero to this value. In the figure, the present fixed useful output coupling is given for comparison. Measured optical properties of CVD-diamond in terahertz range are presented in [7]. They allow an installation of the material into optical resonator.

Thus, in the future the NovoFEL output power can be increased more than two times with such sufficiently large CVD-diamond film.

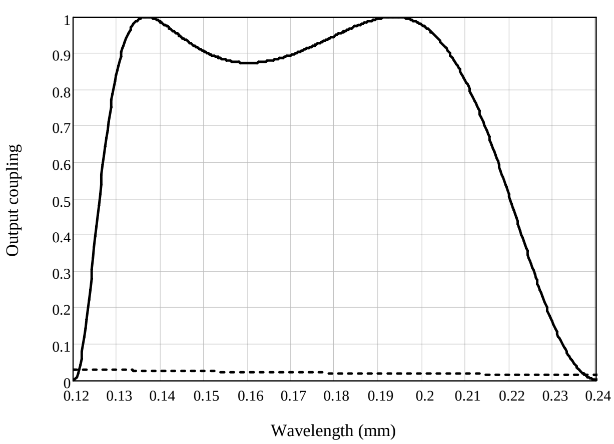

Figure 7: Maximal output coupling of tunable CVD-diamond Michelson output coupling system (solid line) and present fixed output coupling through openings (dashed line).

CONCLUSION

Losses in the NovoFEL optical resonator were measured in its operating range. There is a good agreement between the measurements and a theory which was used for design of the optical resonator. On basis of the theory, upgrade the optical resonator is proposed. The uniform tunable CVD-diamond output coupling system can increase the NovoFEL output power more than two times.

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