J Infrared Milli Terahz Waves (2011) 32:1236–1242
DOI 10.1007/s10762-011-9788-3

Third Harmonic Lasing on Terahertz NovoFEL

V. V. Kubarev · G. N. Kulipanov · O. A. Shevchenko · N. A. Vinokurov

Received: 30 November 2010 / Accepted: 5 April 2011 /
Published online: 13 April 2011

Abstract The lasing at the third harmonic of the fundamental frequency, at a wavelength of about 70 μm, was recently achieved on Novosibirsk terahertz free electron laser. Choosing various optical resonator losses for the fundamental and third harmonics as well as the resonator length, one can force the lasing to occur at both the frequencies simultaneously or at either of them alone.

Keywords Free electron laser · High harmonic lasing · Terahertz radiation

1 Introduction

The lasing at high harmonics is important for the free electron lasers because it is the simplest way to expand their spectral range. In certain cases, switching between the generation regimes at the fundamental or high harmonics can be realized via a simple manipulation with the optical resonator.

The first generations at the third harmonic of the free electron laser in the infrared range were achieved in 1988 [1, 2]. The third harmonic lasing was demonstrated at many laboratories since then. The generation at the second [3], third and fifth [4] harmonics in the IR range was studied at Jefferson Lab recently. A common requirement for the lasing at a single high harmonic is, first, a sufficiently high gain, which should be higher than the resonator loss, and, second, a gain/loss relation more favorable for the high harmonic than for the fundamental one. The simultaneous lasing on both the harmonics is possible if the generation conditions for both harmonics are approximately the same.

Earlier we reported achieving a power of the second and third harmonic radiation amounting to a few percent of the power of the fundamental harmonic on terahertz NovoFEL [5]. We found the optimal conditions for the amplified spontaneous emission at the harmonics [6].

V. V. Kubarev (✉) · G. N. Kulipanov · O. A. Shevchenko · N. A. Vinokurov
Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
e-mail: V.V.Kubarev@inp.nsk.su

In this paper, the experimental results of the third harmonic lasing on terahertz NovoFEL are presented.

2 THz NovoFEL design and diagnostics

Terahertz NovoFEL is based on the 12-MeV energy recovery linac with an average current of up to 20 mA. The peak current of the accelerator reaches 10 A in continuously repeated 100-ps pulses. The electron beam radiates THz waves into two 32-pole undulators with a period of 12 cm and the maximum parameter $K = 1.25$ [7].

The optical resonator of terahertz NovoFEL has an open geometry (Fig. 1) [8]. It is formed by two 15-m spherical mirrors located with a spacing of 26 m. The mirrors have central apertures of 3.5 mm and 8 mm in diameter for optical alignment and output of the laser radiation. The three pairs of diaphragms shown in Fig. 1 are the narrowest places of the vacuum chamber of our optical resonator. They have a special absorbing ceramic coating to avoid beam reflection and undesirable intracavity interference. The movable scraper mirrors, initially designed for intracavity calorimetry [8], now are also used to optimize the third harmonic lasing.

The NovoFEL radiation is transported to the user hall by the 40-m optical beam line with plane and toroidal mirrors. The tube of the beam line is filled with a continuously dried air/nitrogen mixture.

The diagnostics system used in the experiments consisted of a vacuum Fourier spectrometer [9], various detectors, and metallic dichroic filters [10] for the separation of the first and third harmonics. A two-dimensional imaging system based on a thermo-fluorescent screen [11] was used to measure the intensity distribution of the output laser beams.

3 Simplest theory of harmonic lasing

Terahertz NovoFEL, as shown in [8], can be presented in the first estimation as a uniform broadened laser. The following correlation is true for its output power:

$$P \propto \frac{G}{\gamma} - 1, \qquad (1)$$

where G is the unsaturated gain and γ is the loss per round trip of light in the optical resonator. As is well known, a harmonic gain appears in a plane undulator as a result of an

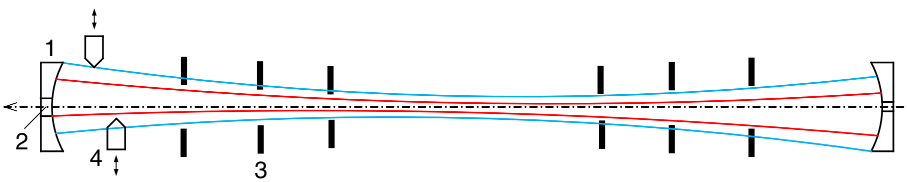


Fig. 1 Scheme of the optical resonator of terahertz NovoFEL: 1 – the mirrors, 2 – the central apertures in the mirrors, 3 – the absorbing diaphragms, 4 – the scraper mirrors. The contours of the first- and third-harmonic beams are shown with the blue and red lines, respectively.

anharmonic electron radiation caused by a modulation of the longitudinal velocity of the electrons. According to [12], the harmonic gain is in the following correlation:

$$G_f \sim f \cdot K_f^2, \tag{2}$$

where $f = 1, 3, 5 \ldots$ and

$$K_f(\xi) \equiv K \cdot (-1)^{\frac{f-1}{2}} \cdot \left[J_{\frac{f-1}{2}}(f\xi) - J_{\frac{f+1}{2}}(f\xi) \right] \tag{3}$$

$$\xi \equiv \frac{K^2}{4(1 + K^2/2)} \tag{4}$$

$$K = \frac{eBL}{2\pi \cdot mc^2} \tag{5}$$

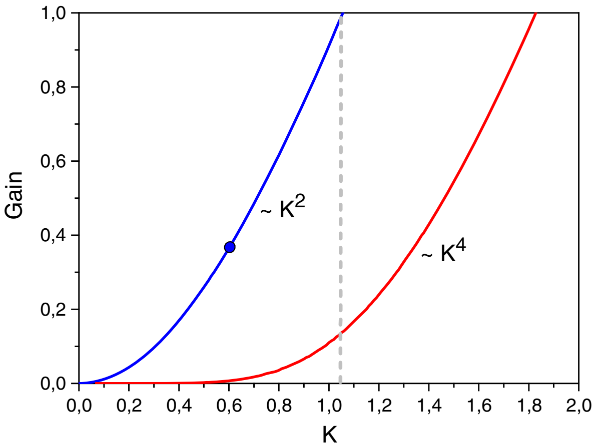
In relations (3)-(5) J_i is the Bessel function; K is the undulator parameter; B and L are the magnetic field and period of the undulator, respectively.

The gains of the first and third harmonics calculated by the above formulas are presented in Fig. 2. The absolute values of the gains were normalized to the experimental point $K = 0.6$, $G = 0.36$ [13]. One can see that an essential third harmonic gain appears only for a sufficiently large parameter K or in the long-wave range of NovoFEL. The real value of the parameter K in our third harmonic lasing experiment is marked with the vertical dash line.

The loss in the NovoFEL optical resonator was determined by the simple analytical method described in [14]. The method has a good accuracy for a round-trip loss of up to 20%. For a larger loss, this method can also be used, for rough estimations. The results of the calculations are shown in Fig. 3. Here the loss is presented as a function of S, the shift of the mode center from the mirror center, for the working wavelengths of the first and third harmonics of 207 μm and 68 μm, respectively. The optimal experimental shift for the best third harmonic lasing is marked with the vertical dash line.

The minimum of the third harmonic loss appears in consequence of the decrease in the loss in the central mirror apertures due to a certain increase in the shift.

Fig. 2 Gain of the first (blue line) and third (red line) harmonics versus the undulator parameter *K*.



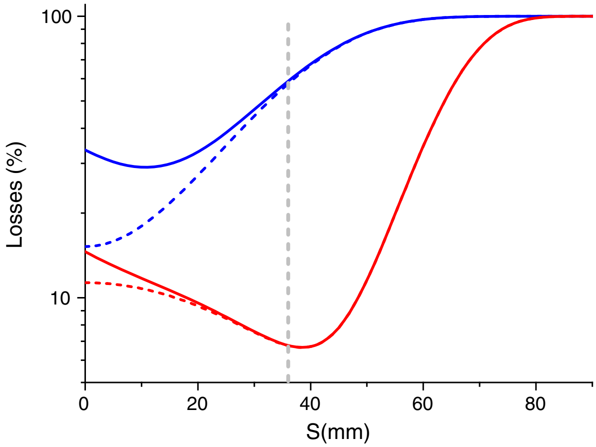


Fig. 3 Loss per round trip for the first (blue lines) and third (red lines) harmonics versus *S*, the shift of the mode center from the mirror center: with the scraper removed (dash lines) and partly inserted (solid lines).

4 Experimental results

A typical procedure to obtain the lasing at the third harmonic of terahertz NovoFEL in the long-wave region of its spectral range was as follows. After optimization of the electron beam, we inserted one scraper mirror into the periphery of the fundamental intracavity optical beam until its generation was fully suppressed. Then we tilted the opposite mirror of the optical resonator in order to move the optical resonator axis away from this scraper mirror. For some optimal tilt, the stable third harmonic lasing (Fig. 4c) was achieved because the intracavity loss for the third harmonic became much smaller than for fundamental harmonic. The smaller cross-section of the third harmonic beam allowed us to optimize the output radiation coupling via the tilt as well [13].

The output CW power of the third harmonic radiation was approximately the same as that of the fundamental one. In the routine NovoFEL regime (with a repetition frequency of the electron beam of 5.6 MHz) the power was 30 W. The maximum pulse power of the third harmonic was about 50 kW. The simultaneous generation of the first and third harmonics in different proportions was also possible with the scraper partly or fully removed (Fig. 4b). The simultaneous lasing at both the harmonics can be used in some pump-probe experiments because the harmonics can be efficiently filtered with dichroic filters [9].

The third harmonic radiation is much more sensitive to the quality of the electron beam alignment and intracavity light coherence [6]. However, for a carefully aligned electron beam, the third harmonic lasing was so stable that it was impossible to achieve a pure first harmonic radiation by manipulations with the optical resonator only.

The spectra of the first and third harmonic laser generation as well as amplified spontaneous emission at the third harmonic are shown in Fig. 5. Both the spectra of the third harmonic radiation have a width that is three times less than the spectral width of the first harmonic. An interesting feature of the third harmonic laser line is a 2% shift from the three-fold fundamental frequency towards the higher frequency. A shift of approximately the same 1.6% was described in paper [1], where this phenomenon was explained by the asymmetry and distortion of the FEL gain curve in the saturated regime.

The curves of detuning between the repetition frequencies of electron and light pulses inside the optical resonator are shown in Fig. 6. The real power of the amplified spontaneous emission of the third harmonic for the carefully aligned regime amounted to a

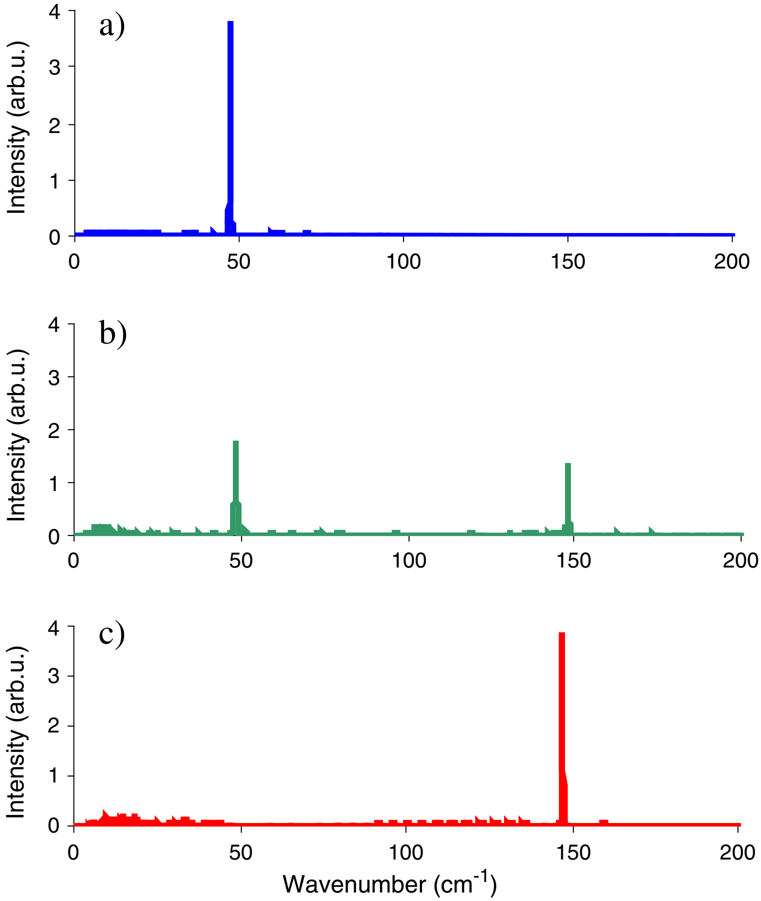
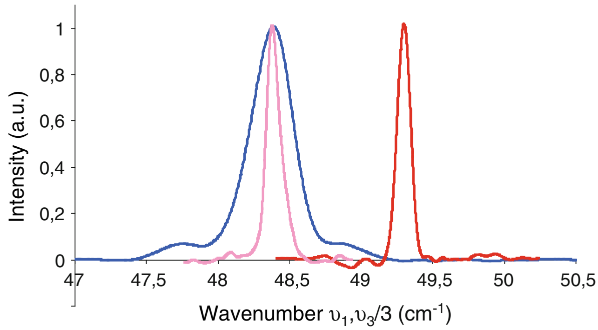


Fig. 4 Spectra of the terahertz NovoFEL radiation at generation at the first harmonic only (**a**), at the first and third harmonics simultaneously (**b**), and at the third harmonic alone (**c**).

few percent of the first harmonic power, and the shapes of the both detuning curves were practically identical. Such power of the amplified spontaneous emission was sufficient for many user applications, and was, in principle, available throughout the spectral range of

Fig. 5 Spectral lines of the first (blue) and third (red) harmonic lasing and the line of the amplified spontaneous emission of NovoFEL (pink).



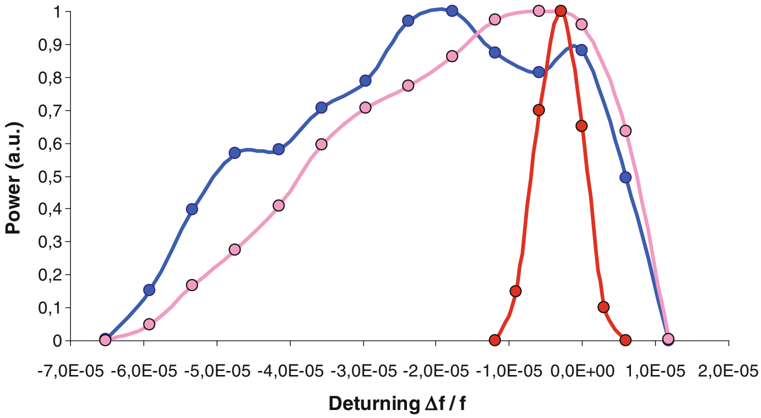


Fig. 6 Normalized detuning curves for the lasing at the first (blue) and third (red) harmonics and the detuning curve for the amplified spontaneous emission at the third harmonic (pink).

terahertz NovoFEL. The third harmonic lasing has a much narrower detuning range. Now this lasing is available only in the long-wave region of terahertz NovoFEL due to the strong dependence of the third harmonic gain on the undulator parameter K (Fig. 2).

Two-dimensional images of the beam intensities are presented in Fig. 7. One can see than both the laser beams are Gaussian-like and similar. The difference in the beam sizes is caused by the difference in the focusing parameters of our optical beam line for the first- and third-harmonic wavelengths. The small ellipticity of the beams can be due to the small difference in the sagittal and meridional focal lengths of the last toroidal mirror in our beam line. The parameter M^2 of both the laser beams in the sagittal and meridional directions did not exceed 1.2.

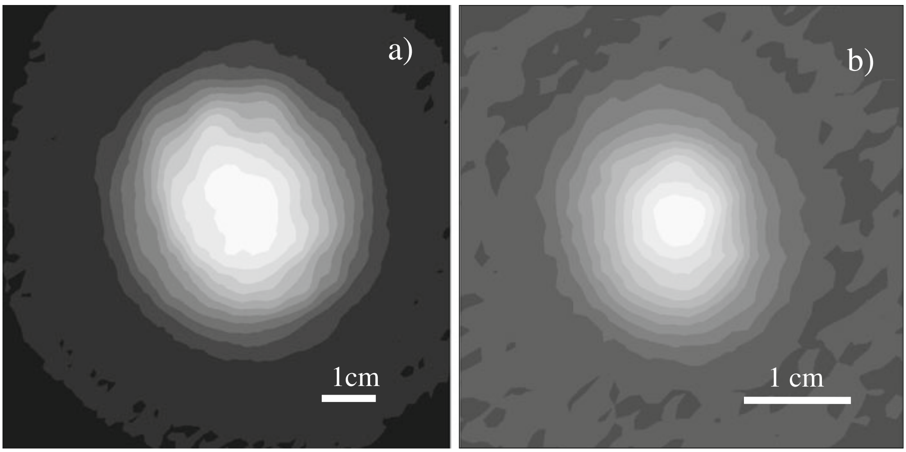


Fig. 7 Beam intensities at the first (**a**) and third (**b**) harmonics at the metrology station of NovoFEL. The difference in the intensities of the neighboring contours is 10%.

5 Conclusions

The stable third harmonic lasing of terahertz NovoFEL with a CW power of 30 W and a pulse power of 50 kW at a wavelength of about 70 μm was demonstrated and investigated.

Acknowledgements This work was supported partly by the Russian Foundation For Basic Research (project 09-02-12121, 10-02-085-18).

References

1. S.V. Benson, J.M.J. Madey, "Demonstration of harmonic lasing in a free-electron laser", Phys. Rev. **A39**, 1579–1581 (1989).
2. R.W. Warren, L.C. Haynes, D.W. Feldman, W.E.,Stein, S.J. Gitomer, "Lasing on the third harmonic", Nucl. Inst. & Meth. **A296**, 84–88 (1990).
3. G.R. Neil, S.V. Benson, G. Biallas, J.Gubeli, K.Jordan, S. Myers, and M.D. Shinn, "Second harmonic FEL oscillation", Phys. Rev. Lett. **87**, 084801(1–4) (2001).
4. S.V. Benson, M.D.Shinn, "Harmonic lasing characterization at Jefferson Lab", Proc. FEL 2006, BESSY, Berlin, Germany, 323–326 (2006).
5. V.V. Kubarev, N.A. Vinokurov, V.V. Kotenkov, G.N. Kulipanov, A.N. Matveenko, T.V. Salikova, S.S. Serednyakov, M.A. Scheglov, "Harmonic generation in the Novosibirsk terahertz free electron laser", Proc. IRMMW-THz 2006, Shanghai, China, 162 (2006).
6. V.V. Kubarev, G.N. Kulipanov, E.I. Kolobanov, A.N. Matveenko, L.E. Medvedev, V.K. Ovchar, T.V. Salikova, M.A. Scheglov, S.S. Serednyakov, N.A. Vinokurov, "Modulation instability, three mode regimes and harmonic generation at the Novosibirsk terahertz free electron laser", Nucl. Instr.&Meth. **A 603**, 25–27 (2009).
7. N.G. Gavrilov, B.A. Knyazev, E.I. Kolobanov, V.V. Kotenkov, V.V. Kubarev, G.N. Kulipanov, A.N. Matveenko, L.E. Medvedev, S.V. Miginsky, L.A. Mironenko, A.D. Oreshkov, V.K. Ovchar, V.M. Popik, T.V. Salikova, M.A. Scheglov, S.S. Serednyakov, O.A. Shevchenko, A.N. Skrinsky, V.G. Tcheskidov, N. A. Vinokurov, "Status of the Novosibirsk high-power terahertz FEL", Nucl. Instr.&Meth. **A 575**, 54–57 (2007).
8. V.V.Kubarev, B.Z.Persov, N.A.Vinokurov, A.V.Davidov, "Optical resonator of powerful free- electron laser", Nuclear Instr. & Meth. **A 528**, 199–202 (2004).
9. V.V. Kubarev. N.A. Vinokurov, E.I. Kolobanov, V.V. Kotenkov, G.N. Kulipanov, A.N. Matveenko, T.V. Salikova, S.S. Serednyakov, M.A. Scheglov, "Fourier spectroscopy of water vapor absorption in 40 m optical transport channel of the NovoFEL", Proc. IRMMW-THz 2007, Cardiff, UK, 978–979 (2007).
10. S.A. Kuznetsov, V.V. Kubarev, P.V. Kalinin, N.A. Vinokurov, "1-D and 2-D metal mesh based quasi-optical selective components for high-power applications at Novosibirsk terahertz FEL ", Proc. IRMMW-THz 2007, Cardiff, UK, 303-304(2007).
11. V.V. Kubarev, E.V. Makashov, K.S. Palagin, S.S. Serednyakov, M.G. Fedotov, "Powermeters and 2D beam imaging systems on the Novosibirsk terahertz free electron laser", Proc. IRMMW-THz 2007, Cardiff, UK, 249–250 (2007).
12. W.B.Colson, "The nonlinear wave equation for higher harmonics in free-electron lasers", IEEE J. Quantum Electronics **QE-17** (8)**,** 1417–1427 (1981).
13. V.V. Kubarev, "Calculation, optimization, and measurements of optical resonator parameters of the Novosibirsk terahertz free-electron laser", Quantum Electronics **39** (3), 235–240 (2009).
14. V.V. Kubarev , "Babinet principle and diffraction losses in laser resonators", Quantum Electronics **30** (9), 824–826 (2000).