Tunable narrowband terahertz emission from mastered laser-electron beam interaction

S. Bielawski[3], C. Evain[3], T. Hara[6] , M. Hosaka[1], M. Katoh[1,2], S. Kimura[1,2], A. Mochihashi[1,2], M. Shimada[1], C. Szwaj[3], T. Takahashi[5] and Y. Takashima[4]
1: UVSOR, Institute for Molecular Science, Okazaki, Aichi, 444-8585, Japan.
2: School of Physical Sciences, The Graduate University for Advanced Studies (SOKENDAI), Okazaki, Aichi, 444-8585, Japan.
3: Laboratoire PhLAM, UMR CNRS 8523, CERLA, FR CNRS 2416, Université des Sciences et Technologies de Lille, 59655 Villeneuve d'Ascq Cedex, France.
4: Graduate School of Engineering, Nagoya University, Nagoya, 464-8603, Japan.
5: Research Reactor Institute, Kyoto University, Kumatori-cho, Osaka, 590-0494, Japan. and
6: Visiting researcher in UVSOR[1], permanent address: SPRING-8/RIKEN, Sayo-cho, 679-5148 Hyogo, Japan.
(Dated: January 8, 2008)

PACS numbers: 41.75.Ht, 41.60.-m, 42.65.-k

In the quest for sources of optical radiation in the terahertz domain, promising candidates are nonlinear optical processes occurring when an intense laser beam interacts with a material medium [1–5]. Besides conventional media (as crystals), relativistic electrons also appear to exhibit striking nonlinear collective behaviors, which can lead to powerful laser-induced coherent emission [6, 7], revealing huge potentials of these devices as terahertz sources [8]. However, up to now only broadband emissions were reported, and experimental control of their radiation properties, as their spectra [9, 10], remained an important challenge. Here, we demonstrate the possibility to master experimentally the coherent emission by producing tunable narrowband terahertz radiation. The interaction is made to occur between an electron beam and laser pulses possessing a longitudinal quasi-sinusoidal modulation, and the narrowband emission occurs in a region of quasi-uniform magnetic field. The process therefore strongly differs from classical synchrotron radiation experiments, where narrowband emission occurs inside a periodic magnetic field.

Terahertz generation in classical media has a long history [1]. The fundamental processes involved, in particular optical rectification, current transients in semiconductors, and difference frequency mixing, have been extensively studied both theoretically and experimentally, some of them since the sixties [3]. Now, nanojoule to microjoule energies can be obtained in broadband sources [1, 4, 5], and narrowband emission based on laser pulse-shaping [11–15] is also a well studied technique. Besides, THz emission using laser-electrons interaction (laser-induced charge density modulation) is a very new field. First results on broadband THz emissions using short pulse laser slicing in an undulator have been reported during the two last years [6, 7, 10, 16, 17]. Slightly before, Carr et al. [8] addressed the very related question of power attainable by fastly modulated charge densities (a very short electron bunches in this case). This research field needs now experimental investigations at the very fundamental level, concerning in particular the actual feasibility of interaction processes, their potentials, as well as their fundamental limits.

In laser-electron beam interaction, the technical arrangement presents similarities with THz emission experiments in classical materials. However the physics strongly differs and involves complex evolutions of the electrons in phase-space, specific to the so-called laser-induced slicing [6, 7, 10, 16, 17].

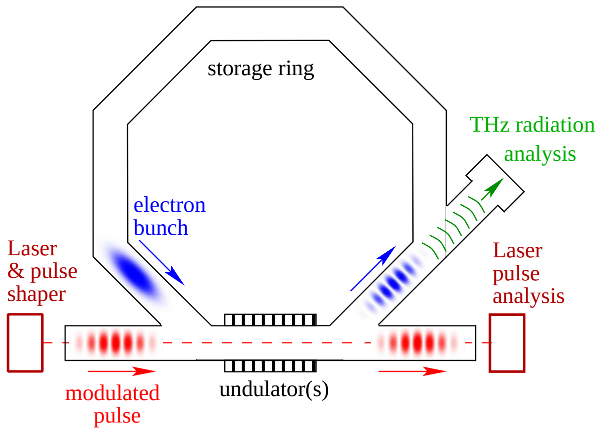

FIG. 1: Principle of the experiment. A laser pulse (at 800 nm) is shaped to display a longitudinally sinusoidal modulation, with a period in the picosecond-range. The pulse interacts with the electron bunch of an accelerator (the UVSOR-II storage ring here), in a region of periodic magnetic field (an undulator tuned at the laser wavelength). The electron bunch is then deviated by a dipole magnet, and terahertz emission occurs with a process similar to classical laser-induced slicing coherent synchrotron radiation[6, 7, 10, 16, 17].

The principle of our experiment is illustrated in Fig. 1. A laser pulse with a quasi-sinusoidal envelope interacts with the electron bunch of a storage ring, in a region of periodic magnetic field (an undulator tuned at the laser wavelength). In this first step (Figs. 2a,b), the electrons mainly experience a fast energy modulation at the optical scale (not resolved in Fig. 2), whose amplitude is quasi-sinusoidally modulated at a terahertz frequency. Then, the electrons pass through a bending magnet, where they

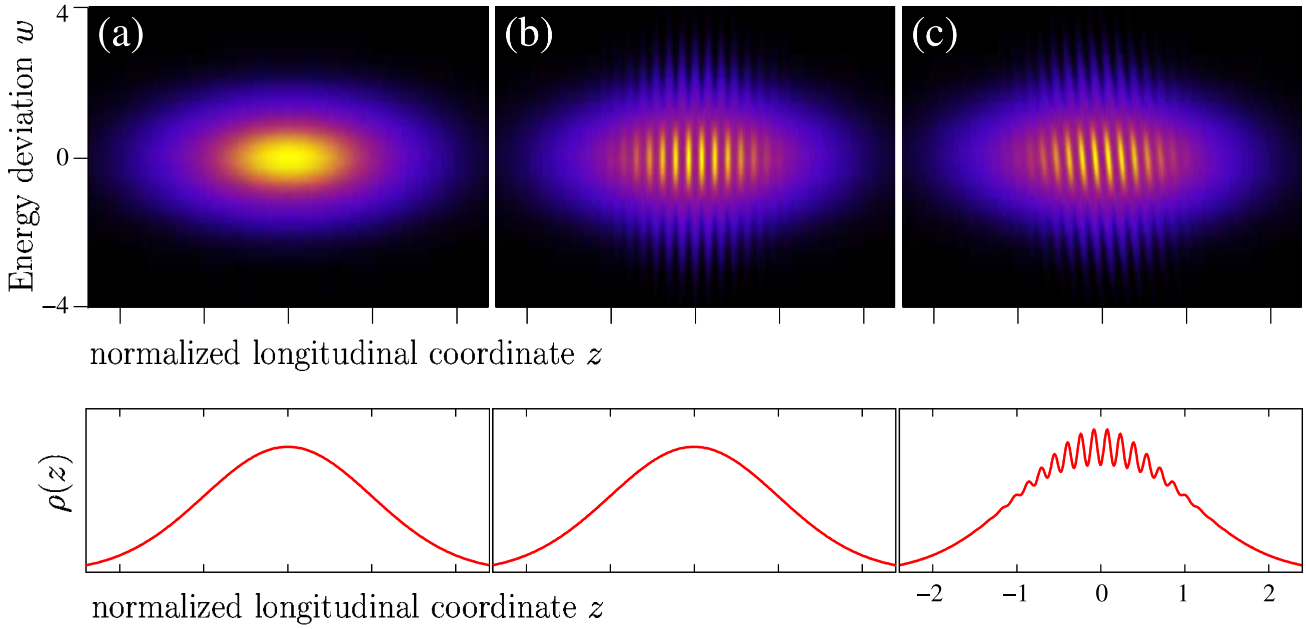

FIG. 2: Illustration of the narrowband terahertz generation process. Electron bunch phase-space distributions (upper images) are represented with their associated longitudinal charge density distributions $\rho(z)$. z and w are the electrons's longitudinal position and energy deviation respectively expressed in units of their RMS values before interaction. (a) distribution before interaction. (b) just after interaction with the laser in the undulator, modulations are visible in phase space, but do not affect noticeably the charge distribution. After visiting the next magnetic field section (c), the distribution is "tilted". $\rho(z)$ is then longitudinally modulated, and strongly radiates. A fast oscillation, not visible at this scale, is also present (see theoretical section for details).

experience different trajectories. As a result, the phase-space distribution is "tilted" as shown in Fig. 2, leading to a longitudinal charge modulation, which in turn induces strong terahertz emission. The emission frequency is equal to the laser pulse modulation frequency.

Although the desire to realize experimentally such processes was reported some times ago through theoretical/numerical works by our group[9] and the LBNL laboratory[10], and although recent experiment with short (unmodulated) pulses were successful [6, 7, 10], experimental evidence of terahertz emission in the modulated case still remained an open question. A main reason probably stemmed from the initial project to use -instead of sinusoidal modulations- a series of laser pulses, which can be delicate to produce[9, 10]. Here, a key point consisted to use a pulse shaping technique widely used in solid-state terahertz sources [12–15], *chirped pulse beating*[11] (see methods), to produce the pulses incident on the electron bunch. Compared to the setups envisaged for multiple pulse generation[18], chirped pulse beating allows to obtain a sinusoidal modulation with a widely scalable period T_m , and pulse duration T_D using a simple (and robust) setup, compatible with accelerator environments. The pulse duration could be varied from several picoseconds to 100 ps, and we examined the terahertz emission for a wide range of modulation periods. The pulse repetition rate was 1 kHz and the incident energy was typically in the 0.1-0.5 mJ range.

Experiments quickly revealed strong tunable terahertz emission when the period T_m was in the 1-2 ps range. First experiments were performed using pulses with relatively short durations and high peak powers (≈2 ps, 0.5 mJ), in order to start with conditions close to the already mastered laser slicing[6, 7, 16, 17]. Then we chose to increase the pulse train duration up to 60 ps using a grating stretcher (see methods). This increased strongly the number of modulation periods, and allowed to reduce drastically the spectrum width of the emitted terahertz radiation from ≈ 4 cm^{-1} to ≈ 1 cm^{-1}. Typical terahertz spectra obtained in these conditions are displayed on Fig. 3a. Compared to conventional laser-induced slicing coherent synchrotron radiation (CSR), it is important to note that the effect was obtained with a peak power dramatically lower, because of the larger pulse durations used here (60 ps instead of typically 50 fs-2 ps in classical CSR[6, 7, 16]), and because of the energy loss introduced by the standard-quality gratings used in the pulse-shaper.

Tunability is possible simply by adjusting one Michelson retroreflector position (see methods). In addition to potential applications, this allows to check the consistency between the internal modulation frequency of the laser pulse, and the emitted peak frequency (they should be theoretically equal). Consistency was found at various pulse durations and beam currents, a typical curve being represented in Fig. 3b. All results hence confirm that the process involved in the narrowband terahertz emis-

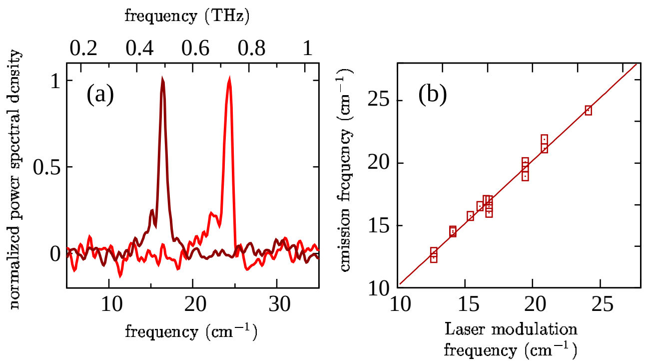

FIG. 3: Typical narrowband THz emission spectra and tunability curve. (a) Two terahertz spectra obtained with a 60 ps long pulse for and two positions of the Michelson interferometer corresponding to modulation frequencies of the laser pulse of 16 cm^{-1} and 24 cm^{-1} respectively. The pulse energy at the undulator is of the order of 130 μJ. (b): peak emission frequency versus laser pulse modulation frequency (obtained with pulses of 2 ps and 60 ps). The full line is the 45 degree line.

sion corresponds to the modulated-pulse-induced CSR. A detectable peak was found from modulation frequencies in the 12-25 cm^{-1} range.

From a theoretical point of view, the terahertz emission wavelength range can be estimated from a rather simple approach[10, 19–21]. The radiated THz field is closely related to the longitudinal electron distribution $\rho(z)$, which acts as a source in the process. In particular it is possible to get the following approximation for the spectrum, i.e the Fourier transform $R(k)$ of the longitudinal charge distribution $\rho(z)$ valid in the THz region:

$$R(k) \approx (2\pi)^{-1/2} e^{-(r_{51}^2+r_{52}^2+r_{56}^2)k^2/2} \times \int_{-\infty}^{+\infty} e^{-ikz} e^{-z^2/2} J_0(kr_{56}a(z))dz \quad (1)$$

where the r_{ij} are normalized coefficients associated to the transport matrix elements R_{ij}[19]. J_0 is the Bessel function of zero order. For the present purpose, we have examined the response to a Gaussian pulse of RMS width σ_L, that induce a variation w_0 of the energy multiplied by a sinusoidal modulation:

$$a(z) = w_0 e^{-(z/2\sigma_L)^2} \cos(k_m z/2 + \phi) \quad (2)$$

where k_m represents the wavenumber of the intensity modulation. As expected and in agreement with experimental data, numerical integration reveals that, at small values of w_0, the response is mainly a single peak at k_m (Fig. 4). The efficiency curve (at moderate w_0) appears bell-shaped. The peak efficiency is found to tend asymptotically to a finite value (24 cm^{-1} for our experimental parameters) in the limit w_0 small (in practice w_0=0.3 or smaller), and this maximum shifts towards lower frequencies when w_0 increases. Asymptotic expressions for the spectrum is beyond the scope of this paper, and will deserve further work. The objective of the present modeling is mainly to provide a simple way through Eq. (1), to anticipate the accessible THz emission range for a set of machine parameters, or to design a system emitting at a desired THz target wavelength.

The feasibility of the process naturally motivates to enter two research directions. The first concerns the optimization of terahertz emission (power, bandwidth, etc.), and the identification of technical and fundamental limits. For the moment, the typical arrangement presented here —which was destinated to feasibility studies and not optimized for high power generation— provided a brilliance comparable to commercial sources such as the Teraview (in the nJ/cm^{-1} range) at currents of the order of 20 mA. However straightforward improvements are expected to increase the emitted power and brillance. Key points of the powers reachable by optimized setups have been discussed in recent papers (see in particular [8]), and these topics will hence not be addressed here in detail. However increases by orders of magnitude are expected to be obtained by elementary optimizations of overlap, incident power, current density in the storage ring, in particular because of the quadratic scaling of terahertz power with laser intensity and bunch charge density. A second, more fundamental interest concerns the use this type of experiment as a “probe” to investigate the electron beam nonlinear dynamics and instabilities. Spatiotemporal instabilities are indeed of importance because they limit the operation of storage rings at high current. Theories predict the occurrence of instabilities through the growing of unstable modes in a way similar to pattern-forming systems [22], and responses to sinusoidal perturbations are a fundamental point of the instability processes. However direct experimental tests of these theories still represent big challenges, because phase-space evolutions in a storage ring are usually not observable directly in real time, and also because methods for selectively perturbating short wavenumbers were lacking up to now. Since the type of experiment described here gives the possibility to imprint periodic wave patterns inside the electron bunch phase space, and to follow phase-space modulations by monitoring the emitted terahertz radiation, we think that this opens the way to new direct tests of current models, e.g., by providing information on growth/relaxation rates of perturbations versus wavenumber [20, 21].

Methods

The laser pulses are produced by a usual commercial Sapphire-Titanium laser chain (coherent Mira 900-F and Legend F-HE), delivering 2.5 mJ pulses at 1 kHz, which can be compressed down to 130 fs. To stretch and modulate these pulses, we used the system of chirped pulse beating[11], represented in Fig. 5. A stretcher based on a grating pair (standard 1200 lines/mm, size 50 mm, 70 and 80% efficiency) induces a strong negative chirp and

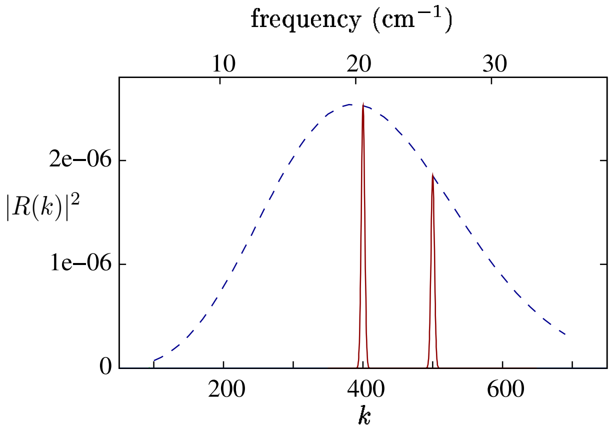

FIG. 4: Calculated efficiency versus THz modulation frequency. The two peaks (full lines) are spectra associated to modulation frequencies of $k_m = 470$ and $k_m = 600$ respectively. The dashed curve represents the peak value versus modulation frequency. The r_{ij} parameters are the typical ones for the present UVSOR-II experiment: $r_{51} = 5.3 \times 10^{-4}$, $r_{52} = 2.1 \times 10^{-3}$, $r_{56} = 2.9 \times 10^{-3}$, and the bunch RMS length is 3.1 cm. Laser parameters are: $w_0 = 0.3$, $\sigma_L = 0.3$, $\phi = 0$.

increases strongly the pulse duration (in the 5-100 ps range here). Then, two copies of the pulse are made to interfere with an adjustable delay τ in a Michelson interferometer. This leads to a pulse with a quasi-sinusoidal temporal modulation whose frequency is proportional to τ (see Ref. 11 for details).

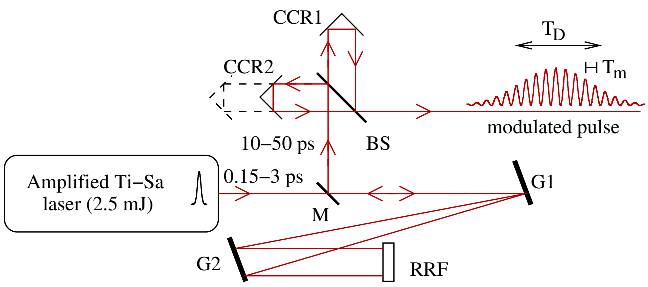

FIG. 5: Detail of the pulse shaper. G1 and G2: 1200 lines/mm gratings. M: 45^o mirror, RRF: roof retro-reflector. CCR1 and CCR2 are high precision corner-cube retroreflectors. Focusing of the modulated pulse is performed by a lens with 5 m focal length, placed ≈4 m after the pulse-shaping system.

As an important point, the Michelson interferometer is provided with two precision corner-cube retro-reflectors (parallelism < 1 arc sec), in order to keep a good overlap after the large propagation distance (of the order of 10 m) to the undulator. The stretching is provided by the grating pair for long pulse operation. For the experiments with shorter pulse widths (typically < 5 ps) we did not use this grating pair, and simply adjusted the amplifier's internal grating pair distance. With this setup, the total duration T_D is adjustable in the 150 fs-100 ps range, and for a given pulse duration the modulation period T_m is typically adjustable between 150 fs and T_D.

The terahertz emission is analyzed at the beam line BL6B[23] using an in-vacuum Martin-Puplett FTFIR spectrometer, which allows the recording of spectra in the 2-55 cm^{-1} range with a resolution of 0.5 cm^{-1} and is detected by an InSb bolometer (QMC Instr. LTD, QFI/2).The pulse processing is made using a gated integrator (SRS250) in order to reduce background from normal synchrotron radiation. The gated integrator is triggered by the same 1 kHz oscillator as the Ti:Sa laser and the width was chosen around 1 μs which correspond to the response time of the InSb bolometer. The UVSOR-II storage ring was operated in single bunch mode at 600 MeV, with a bunch duration of ≈ 80 ps RMS. The experiment was performed at various currents in the 0-40 mA range (i.e., with a bunch charge in the 0-7 nC range), to avoid beam instabilities and spontaneous CSR[24].

We would like to thank M.-E. Couprie for stimulating discussions and all the UVSOR staff for their help. This work was supported by the Joint Studies Program (2005-2007) of the Institute for Molecular Science, and the JSPS fellowship program for research in Japan (grant S06215) by Grant-in-AID for Scientific Research B15360038 and B15360039 of JSPS and by the research foundation for Opt-Science and Technology. The CERLA is supported by the French Ministère chargé de la Recherche, the Région Nord-Pas de Calais and the FEDER.

[1] Reimann, K. Table-top sources of ultrashort THz pulses. *Rep. Prog. Phys.* **70**, 1597 (2007).
[2] Williams, G. Filling the THz gap-high power sources and applications. *Rep. Prog. Phys.* **69**, 201 (2006).
[3] Zernike, F. & Berman, P. Generation of far infrared as difference frequency. *Phys. Rev. Lett.* **15**, 999–1001 (1965).
[4] F. Blanchard *et al.* Generation of 1.5 μJ single-cycle terahertz pulses by optical rectification from a large aperture ZnTe crystal. *Optics Express* **15**, 13212 (2007).
[5] G. Imeshev *et al.* High-power source of THz radiation based on orientation-patterned gaas pumped by a fiber laser. *Optics Express* **14**, 4439 (2006).
[6] Holldack, K., Kachel, T., Khan, S., Mitzer, R. & Quast, T. Characterization of laser-electron interaction at the bessy II femtoslicing source. *Phys. Rev. ST Acc. Beams*

8, 040704 (2005).
[7] Khan, S., Holldack, K., Kachel, T., Mitzner, R. & Quast, T. Femtosecond undulator radiation from sliced electron bunches. *Phys. Rev. Lett.* **97**, 074801 (2006).
[8] Carr, G. *et al.* High power terahertz radiation from relativistic electrons. *Nature* **420**, 153–156 (2002).
[9] Takashima, Y., Katoh, M., Hosaka, M. & Mochihashi, A. Feasibility study of generation of far infrared coherent synchrotron radiation using ultrashort laser pulses at UVSOR. *UVSOR activity report 2002, UVSOR-30, ISSN 0911-5730 (2003)* 56–77 (2003).
[10] Byrd, J. M. *et al.* Tailored terahertz pulses from a laser-modulated electron beam. *Phys. Rev. Lett.* **96**, 164801 (2006).
[11] Weling, A. S. & Auston, D. H. Novel sources and detectors for coherent tunable narrow-band terahertz radiation in free space. *J. Opt. Soc. Am. B* **13**, 2783–1971 (1996).
[12] Tzeng-Fu Kao *et al.* Frequency tunability of terahertz photonic transmitters. *Appl. Phys. Lett.* **88**, 093501 (2006).
[13] Lu *et al.* Terahertz microchip for illicit drug detection. *IEEE Phot. Tech. Lett.* **18**, 2254 (2006).
[14] Chen, L.-J., Kao, T.-F., Lu, J.-Y. & Sun, C.-K. A simple terahertz spectrometer based on a lowreflectivity fabry-perot interferometer using fourier transform spectroscopy. *Optics Express* **14**, 3840 (2006).
[15] Belabas, N., Likforman, J.-P., Canioni, L., Bousquet, B. & Joffre, M. Coherent broadband pulse shaping in the mid infrared. *Opt. Lett* **26**, 743 (2001).
[16] Shimada M. *et al.* Intense terahertz synchrotron radiation by laser bunch slicing at UVSOR-II electron storage ring. *Jpn. J. Appl. Phys.* (2007).
[17] Byrd, J. M. *et al.* Laser seeding of the storage-ring microbunching instability for high-power coherent terahertz radiation. *Phys. Rev. Lett.* **97**, 074802 (2006).
[18] Siders, C. W. *et al.* Efficient high-energy pulse-train generation using a 2n-pulse michelson interferometer. *Appl. Optics* **37**, 5302–5305 (1998).
[19] Schoenlein, R. *et al.* Generation of femtosecond X-ray pulses via laser-electron beam interaction. *Appl. Phys. B* **71**, 1–10 (2000).
[20] Stupakov, G. & Heifets, S. Beam instability and microbunching due to coherent synchrotron radiation. *Phys. Rev. S.T. Accel. Beams* **5**, 054402 (2002).
[21] Stupakov, G. & Heifets, S. Model for CSR induced bursts in slicing. *SLAC-PUB* **5**, 11815 (2006).
[22] Cross, M. C. & Hohenberg, P. C. Pattern formation outside of equilibrium. *Rev. Mod. Phys.* **65**, 851 (1993).
[23] Kimura, S. *et al.* Infrared and terahertz spectromicroscopy beam line BL6B(IR) at uvsor-II. *Infrared Phys. Technol.* **49**, 147–151 (2006).
[24] Takashima, Y. *et al.* Observation of intense bursts of terahertz radiation at UVSOR-II. *Jpn. J. Appl. Phys.* **44**, L1131–L1133 (2005).