Internal Mixing in Active Semiconductor Devices for Room-Temperature Generation of Tunable Continuous-Wave Terahertz Radiation

Alvydas Lisauskas, Mark Dias, Sebastian Belz, Michael Feiginov, and Hartmut G. Roskos

Abstract—**We discuss the potential for creating a room-temperature tunable continuous-wave terahertz source based on nonlinear mixing within the active medium of either a dual-color high-power semiconductor laser or a laser amplifier, preferably operating at telecom wavelengths. By minimization of the terahertz waveguide losses and by enhancement of the second-order nonlinearity of the active media, our simulations indicate that one can expect the output power to reach at least 20 μW at an infrared radiation power of 100 mW per color.**

One of the key obstacles in the development of solid-state lasers for continuous-wave THz frequencies arises from the fact that the thermal energy is comparable with or larger than the energy separation between upper and lower laser levels. The conventional approach for solid-state lasers operating in the THz frequency range (quantum cascade lasers (QCLs) or p-Ge-type lasers) followed up to now is to lower the thermal energy by operating at cryogenic temperatures. Alternatively, several inversionless schemes have been proposed for producing coherent THz radiation at room temperature. Just to name two of them: Bloch-gain lasing [1-3] and frequency downconversion by nonlinear mixing.

Here we discuss the latter, i.e., the potential for creating a room-temperature tunable continuous-wave THz source based on nonlinear mixing directly within a semiconductor laser or amplifier. Our main emphasis lies on the identification and optimization of THz-emission mechanisms in the active gain medium itself, i.e., we do not consider two-section devices with a gain region and a conversion region, but explore only single-section devices where the population inversion may play a central role for the generation of the THz wave. The design target is to optimize the device with respect to high power of both the dual-color laser radiation and the THz radiation.

Research towards efficient down-conversion directly in laser-active media has been going on already for more than a decade. Several device designs have been proposed in the literature [4-9], but till now, the estimated power levels of the down-converted beams have been too low to have the potential for a break-through in practical applications. High free-carrier absorption losses at THz frequencies are among the main limiting factors. The loss limits the effective nonlinear interaction length to the sub-mm range and thus largely destroys the advantage of co-propagation of interacting laser fields over long distances even if the phase-matching between the three interacting waves is optimal.

We show that mixing in active laser media has the potential to produce a THz output power on the order of tens of microwatts at a hundred milliwatt of optical radiation. With such a value, such an emitter would be competitive with other THz sources. The realization of it, however, requires simultaneously (i) minimization of the terahertz losses, (ii) optimization of the phase-matching of fundamental modes (polaritonic phase-matching) [10], and (iii) enhancement of the conversion efficiency by quantum engineering. With respect to the latter point, we explore two approaches, an electrooptic one (involving resonant transitions and coherent wavepacket dynamics, and aiming at an enhancement of the second-order nonlinearity by at least two orders of magnitude as compared with the values of bulk III-V semiconductors), and a photoconductive one (based on classical space-charge oscillation).

The literature lists a number of experimental studies devoted to the effective generation of THz radiation in various nonlinear crystals using short laser pulses. In the case of continuous wave radiation such an approach, however, is very inefficient as the interacting fields of focused radiations are comparatively low at typical power levels of semiconductor lasers. Waveguiding of the laser radiation improves the situation, but by itself is not sufficient to ensure high output powers. If one performs simulations for the ideal lossless case and perfect phase matching, and assumes a waveguide mode with a cross section of 20 μm × 1.5 μm, 100 mW of optical power (pro color), and a 2-mm-long waveguide, one should be

A. Lisauskas is with the Physikalisches Institut, Johann Wolfgang Goethe-Universität Frankfurt, 60435 Frankfurt, Germany (phone: +49-69-798-47211; fax: +49-69-798-47221; e-mail: lisauskas@ physik.uni-frankfurt.de).

M. Dias is with the Physikalisches Institut, Johann Wolfgang Goethe-Universität Frankfurt, 60435 Frankfurt, Germany.

S. Belz is with the Physikalisches Institut, Johann Wolfgang Goethe-Universität Frankfurt, 60435 Frankfurt, Germany.

M. Feiginov is with the Institut für Hochfrequenztechnik, Technische Universität Darmstadt, 64283 Darmstadt, Germany (e-mail: feiginov@hf.tu-darmstadt.de).

H. G. Roskos is is with the Physikalisches Institut, Johann Wolfgang Goethe-Universität Frankfurt, 60435 Frankfurt, Germany (e-mail: roskos@physik.uni-frankfurt.de).

able to generate about 80 nW of THz radiation at 3 THz with the bulk nonlinearity of InP.

Obviously, the bulk second-order nonlinearity does not promise sufficiently high continuous-wave THz power levels to be competitive with the best photoconductive photomixers. The way to go to improve the THz generation efficiency is the engineering of the nonlinearity itself. It is well-known that the value of the second-order nonlinear coefficient $\chi^{(2)}$ increases if the wavelength approaches the absorption edge of the semiconductor. It can be enhanced further by wavefunction engineering. For a high THz conversion efficiency, coupled quantum wells or asymmetric single quantum wells enhance the resonant or near-resonant nonlinearity significantly over the bulk values. In the absorption resonance, a nonlinearity of more than 10^{-8} m/V has been predicted [4], respectively estimated from measurements [11].

We calculate the THz power level under the assumption that the quantum wells of the laser gain medium are replaced by asymmetric structures which both support dual-color lasing and provide a high resonant THz nonlinearity. Our calculations show that, if 200 nm of mode volume of the dual-color laser were filled with a nonlinear medium with $\chi^{(2)} = 2\cdot10^{-8}$ m/V, then a THz power of 38 μW could be achieved with a laser embedded into a double-sided plasmon waveguide with parameters as given before (with waveguide loss of 10.4 cm^{-1}). For a loss-optimized surface-plasmon-polariton waveguide the estimated THz power levels approach the 100 μW regime.

We also propose an alternative way to enhance mixing efficiency by a following photoconductive mechanism. It is based on classical space-charge oscillations, which, if associated with a quasi-static dipole moment, lead to down-conversion of optical radiation. As is usually the case for III-V semiconductors, this requires the presence of a structural or field asymmetry [12,13]. In contrast to conventional photoconductive mixing, we propose the generation of an oscillatory photocurrent in a laser structure with a built-in asymmetry on the basis of the modulation of the stimulated emission with the beat-note of dual-color operation. Because the effect results from photo-depletion of population by stimulated emission rather than from photogeneration of charge carriers, the resultant space charge oscillation may be termed *inverse photocurrent*.

REFERENCES

[1] E. Schomburg, N. V. Demarina, and K. F. Renk, "Amplification of a terahertz field in a semiconductor superlattice via phase-locked k-space bunches of Bloch oscillating electrons", Phys. Rev. B vol. 67, 155302, 2003.

[2] P. G. Savvidis, B. Kolasa, G. Lee, and S. J. Allen. Resonant crossover of terahertz loss to the gain of a Bloch oscillating InAs/AlSb superlattice. Phys. Rev. Lett. vol. 92, 196802, 2004.

[3] A. Lisauskas, C. Blöser, R. Sachs, H. G. Roskos, A. Juozapavicius, G. Valusis, and K. Köhler, "Time-resolved photocurrent spectroscopy of the evolution of the electric field in optically excited superlattices and the prospects for Bloch gain", Appl. Phys. Lett. vol. 86, 102103, 2005.

[4] V. W. Lee and T. K. Gustafson, "Three-wave mixing susceptibility of carrier injected AlGaAs asymmetric quantum wells for mid-infrared difference-frequency generation" Appl. Phys. Lett. vol. 66, p. 271, 1995.

[5] V.Ya. Aleshkin, A.A. Afonenko, and N.B. Zvonkov, " Difference mode generation in injection lasers" Semiconductors vol. 35, p. 1203, 2001.

[6] A. Belyanin, V. Kocharovsky, V. Kocharovsky, and M. Scully, "Three-terminal semiconductor laser for wave mixing" Phys. Rev. A vol. 65, 053824, 2002.

[7] Yu. A. Morozov, I. S. Nefedov, and V. Ya. Aleshkin, "Terahertz oscillator with vertical radiation extraction" Techn. Phys. vol. 49, p. 592, 2004.

[8] Yu. A. Morozov, I. S. Nefedov, V. Ya. Aleshkin, and I. V. Krasnikova, "Terahertz oscillator based on nonlinear frequency conversion in a double vertical cavity" Semiconductors vol. 39, p. 113, 2005.

[9] V. Ya. Aleshkin, A. A. Afonenko, and A. A. Dubinov, "Oscillations at a difference frequency in the middle and far infrareds in gap semiconductor waveguides" Techn. Phys. vol. 51, p. 1207, 2006.

[10] V. Berger and C. Sirtori, "Nonlinear phase matching in THz semiconductor waveguides" Semicond. Sci. Technol. vol. 19, p. 964, 2004.

[11] H. C. Chui, G. L. Woods, M. M. Fejer, E. L. Martinet, and J. S. Harris, "Tunable mid-infrared generation by difference frequency mixing of diode laser wavelengths in intersubband InGaAs/AlAs quantum wells" Appl. Phys. Lett. vol. 66, p. 265, 1995.

[12] S. L. Chuang, S. Schmitt-Rink, B. I. Greene, P. N. Saeta, and A. F. J. Levi", Optical rectification at semiconductor surfaces", Phys. Rev. Lett. vol. 68, p. 102, 1991.

[13] H. G. Roskos, M. C. Nuss, J. Shah, K. Leo, D. A. B. Miller, A. M. Fox, S. Schmitt-Rink, and K. Köhler, "Coherent submillimeter-wave emission from charge oscillations in a double-well potential", Phys. Rev. Lett. vol. 68, p. 2216, 1992.