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Compact All-Quantum-Dot Based Tunable THz Laser Source

Ksenia A. Fedorova, *Member, IEEE*, Andrei Gorodetsky, and Edik U. Rafailov, *Senior Member, IEEE*

***Abstract*—We demonstrate an ultra-compact, room-temperature, tunable terahertz (THz) generating laser source based on difference-frequency-driven photomixing in a coplanar stripline InAs/GaAs quantum-dot (QD) antenna pumped by a broadly-tunable, high-power, continuous wave InAs/GaAs QD laser diode in the double-grating quasi-Littrow configuration. The dual-wavelength QD laser operating in the 1150 nm – 1301 nm wavelength region with a maximum output power of 280 mW and with tunable difference-frequency (277 GHz – 30 THz) was used to achieve tunable THz generation in the QD antenna with a photoconductive gap of 50 µm. The best THz output performance was observed at pump wavelengths around the first excited state of the InAs/GaAs QDs (~1160nm), where a maximum output power of 0.6 nW at 0.83 THz was demonstrated.**

***Index Terms*—Quantum Dots, Semiconductor Lasers, Laser tuning, Terahertz radiation, Antennas, Optical mixers, Photoconductive devices.**

I. Introduction

THE development of a compact, tunable, room-temperature operating, continuous wave (CW) THz source remains one of the key unsolved tasks in the scientific community [1,2]. Various techniques were involved to obtain CW THz radiation. One of the first approaches used CO_2 laser pumped gas lasers, for example, water vapor [3], and many others, including methanol and hydrogen cyanide being the most popular [4]. However, these lasers are extremely bulky and barely support any tunability. The more recent and widely used sources of CW THz radiation are direct quantum cascade lasers (QCLs) [5] and semiconductor mixers of mid-IR QCLs [6,7]. Within the drawbacks of these technologies, though they offer the highest to date wall-plug efficiency, one can mention the following: 1) the need in cryogenic cooling for efficient operation of direct THz QCLs, 2) the lack of broad tunability, 3) the production complexity, and 4) the limitation on the generated frequencies range that barely goes below 2 THz (the most important spectroscopic region covers 1 – 2 THz range). The microwave techniques, involving up-conversion of sub-THz sources, such as Gunn diodes or backward wave oscillators [1] also provide quite efficient generation of non-tunable narrowband THz radiation in the lower-frequency part of the spectrum [8]. The nonlinear mixing in quasi-phase-matched crystals can offer remarkably high THz output power [9], however no tunability can be demonstrated using this approach.

The only technique that can offer the generation of continuously tunable coherent THz radiation is heterodyne mixing of two close optical wavelengths in a semiconductor surface [10,11], which requires a tunable laser pump. Two Titanium-Sapphire [11], or Distributed Bragg Reflector (DBR) filtered diode lasers [12] are usually used for this approach. However, Titanium-Sapphire solid-state lasers, although being perfect tools for the laboratory environment, suffer from well-known drawbacks in terms of size and cost-efficiency, as well as environmental instability and very low power efficiency. This clearly prohibits the field applications of THz systems based on such lasers.

As an alternative, tunable room-temperature THz generation can be achieved by photomixing in a photoconductive (PC) antenna pumped by a dual-color tunable diode laser. Within the last two decades, several techniques have been demonstrated that are capable of delivering a dual-wavelength operation of external-cavity diode lasers. These concepts include the use of a dual-wavelength volume-Bragg grating [13], an Y- or V-shaped slit [14,15], a V-shaped double-stripe mirror [16], or a dual-period holographic element [17] in the laser cavity. Although some of these approaches can offer some tunability of mode separation by moving the position of a slit or a mirror, their tuning ranges are limited. In contrast to the mentioned techniques, the double-grating external-cavity diode laser configuration [18-20] can offer dual-color laser operation with a broadly-tunable mode separation limited only by the spectral bandwidth of its gain element. The highlighted concepts of a dual-wavelength generation are of special interest for a number of applications ranging from biophotonics and wavelength division multiplexing, where the channels of information are encoded on light signals of different wavelengths, to nonlinear frequency conversion, particularly to the visible spectral range by second harmonic generation [21] and to the terahertz region [22] by difference frequency-driven photomixer devices. In this respect, semiconductor lasers, and InAs/GaAs quantum-dot (QD) lasers in particular, with their small size, high efficiency, reliability and low cost can offer broad near-infrared (1 – 1.3 µm) wavelength coverage and wide tunability [23,24], together with the ability to generate two tunable longitudinal modes

Manuscript received September 30, 2016; revised November 24, 2016; accepted November 37, 2016. This work was supported in part by the EU FP7-ICT FAST-DOT project No 224338, the EU FP7-ICT NEXPRESSO program, RFBR grant No 16-07-01166a, and EPSRC grant (EP/H015795/1).

K. A. Fedorova, A. Gorodetsky, E. U. Rafailov are with the School of Engineering & Applied Science, Aston University, AIPT, Aston Triangle, Birmingham, B4 7ET, UK (corresponding author phone: +44(0)121-204-3703; fax: +44(0)121-204-3462; e-mail: k.fedorova@ aston.ac.uk).

E. U. Rafailov is also with ITMO University, 49 Kronversky pr., St. Petersburg, 197101, Russia.

simultaneously [20]. At the same time, InAs/GaAs QD-based antennas capable of being pumped at very high optical intensities of higher than 1W optical power [25], i.e. about 50 times higher than the conventional low-temperature grown material based antennas, allow the development of an all-QD tunable THz laser system.

In this work, we demonstrate the advantage of the use of similar InAs/GaAs QD structures in both the pump laser and the photoconductive antenna for the development of ultra-compact, room-temperature, broadly-tunable THz laser source.

II. Experimental Setup

The experimental setup (Fig.1) consisted of an InAs/GaAs QD laser diode in an external-cavity configuration. The active region of laser chip contained 10 non-identical layers of InAs QDs grown on a GaAs substrate by molecular beam epitaxy in the Stranski-Krastanow mode. The laser chip ridge waveguide had a width of 5μm and a length of 4 mm, and was angled at 5° with respect to the normal of the back facet. Both laser facets had conventional anti-reflective (AR) coatings with total estimated reflectivity of 10^{-2} for the front facet and less than 10^{-5} for the angled facet. The laser chip was mounted on a copper heatsink and its temperature was controlled by a thermo-electric cooler.

As the aim of this work was to demonstrate broadly tunable THz generation in a photoconductive antenna pumped by a dual-wavelength tunable laser, the double-grating quasi-Littrow configuration similar to that described in [20,25] was implemented. In this configuration, the radiation emitted from the back facet of the laser chip was collected with an AR-coated 40x aspheric lens (numerical aperture of 0.55) and then split by a non-polarizing beam splitter into two beams with each one of them coupled onto a diffraction grating (1200 grooves/mm). The diffraction gratings reflected the first order diffraction beams back to the laser chip, thus allowing the simultaneous generation of two wavelengths. The laser output was coupled via an optical fiber into an optical spectral analyzer with the resolution of 0.1 nm and a broadband thermopile power meter.

Initially, the QD laser chip was tested in the single-grating quasi-Littrow configuration [24], and a broad tunability of 182 nm (between 1128 nm and 1310 nm) at room temperature (20°C) and under an operation current of 1.7 A with a maximum output power of 435 mW was achieved, as depicted in Fig. 2. Then the laser chip was tested in the double-grating quasi-Littrow cavity. In this configuration, the dual-color tunability of the QD laser in the wavelength region between 1150 nm and 1301 nm at 20ºC and at a pump current of 1.7 A was made possible by changing the incidence angles of both gratings. Fig. 3 shows the various optical spectra obtained while tuning the dual-color InAs/GaAs QD external-cavity laser across the 1150 nm – 1301 nm wavelength range with a wavelength difference ranging from 1.4 nm to 151 nm, corresponding to the difference frequencies from 0.28 THz to 30 THz, respectively. The resulting optical spectra of each laser mode used for THz generation exhibited a full-width half-maximum spectral bandwidth around 0.5 nm, limited only by the instrumental resolution of the spectrometer used (OSA Advantest Q8383). The minimal achievable wavelength difference between two operating modes was 1.4 nm, and a mode interplay prevented the further reduction of this distance. The two-color laser operation was also confirmed by using the effect of sum-frequency generation in a nonlinear crystal [26] indicating the concurrent generation of both infrared modes in the laser diode. A maximum output power of 280 mW was achieved for the simultaneous dual-wavelength generation at 1230.7 nm and 1232.1 nm, corresponding to the difference frequency of 0.28 THz.

The demonstrated dual-wavelength quantum-dot laser with broadly-tunable difference-frequency (0.28 THz – 30 THz) was used to achieve tunable THz generation in an InAs/GaAs quantum-dot antenna. The PC antenna active region structure comprised 40 layers of InAs QDs, each capped by 4-nm $In_{0.15}Ga_{0.85}As$ and separated by 36-nm GaAs spacer layers, giving a total of 1 μm depth active region. The production of metallic antenna over a semiconductor substrate was done using a standard UV photolithography and a wet etching of the surface Ni/Au (40-nm/200-nm, respectively) features, and a post-process annealing to increase Ohmic contact between the antenna metal and GaAs surfaces was applied. An extra spacer layer of GaAs was grown under the active PC region on an AlAs/GaAs DBR of 30 layers. The need for the DBR is two-fold: to reflect the pump beam thus reducing the IR power at the antenna output, and to allow the possibility for full optical cavity-type optimization of the structure [25]. A coplanar stripline design with a photoconductive gap of 50 μm and an overall contact thickness of 240 nm was used. It should be noticed, that this electrodes design was not optimized for the CW operation, and the fact of successful THz registration assumes a wider range of modernizations, adjustments and optimizations. The laser output was coupled onto the antenna by an AR-coated aspheric lens with a pump-spot width of about 40 μm, thus covering the most of the antenna's photoconductive gap, and centered closer to one of the electrodes for the enhanced operation.

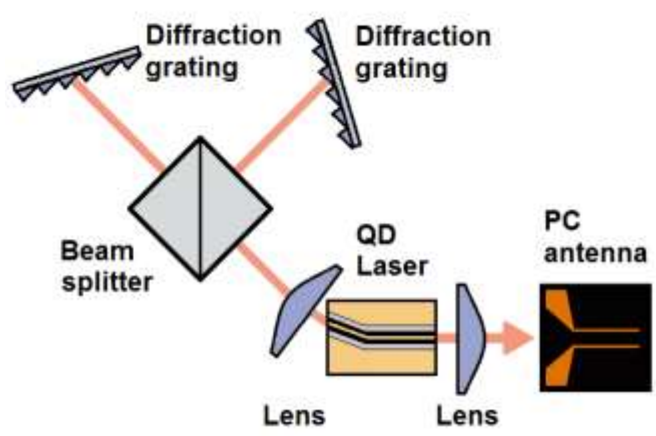

Fig. 1. The simplified schematic of the experimental setup.

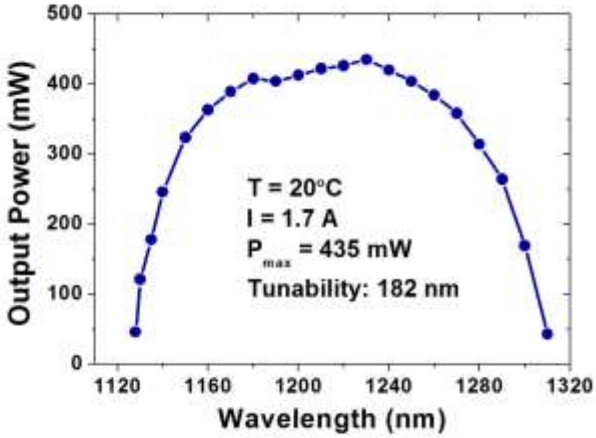

Fig. 2. The dependence of output power on wavelength demonstrated from a QD laser chip in a single grating quasi-Littrow configuration.

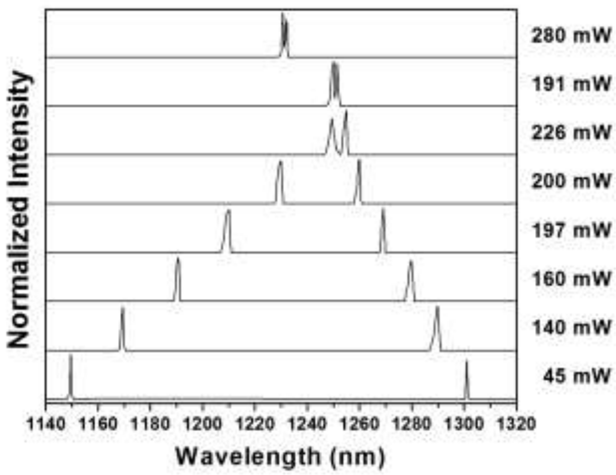

Fig. 3. The normalized optical spectra of the tunable dual-color laser output.

The produced THz radiation was collimated by a hemispherical high-resistive silicon lens and measured with a Golay cell detector (Tydex Ltd), calibrated by a liquid Helium bolometer. To allow the Golay cell operation and eliminate the possibility of signal detection from a possible inter-mode generation (whose difference frequencies lie in the range of around 100 GHz), one of the laser shoulders was chopped at the Golay cell optimal frequency of 14 Hz. The monitored laser output, under chopping didn't reveal any significant power changes, due to the power redistribution into the dual-mode operation when the chopped shoulder is open and the concentration of the full laser power in the single-mode operation with a laser beam way closed by the chopper.

III. Results and Discussion

From our previous experiments [25], efficient THz radiation was expected under the pump in the vicinity of the QD excited states (ES), which for this very wafer, according to the photoluminescence spectrum (Fig.4), are around 1160 nm and at shorter wavelengths. The THz generation efficiency mostly depends on two main parameters of a semiconductor wafer: its photoconductance and carrier lifetimes. First, we measured a conductance of the QD wafer while tuning the wavelength of the single-grating external-cavity QD laser, and these results together with the photoluminescence are shown in Fig. 4. As it can be seen, the normalized (to the pump laser power) conductance peaks correspond to the ground state (GS) and the first ES revealed by the QD antenna structure. Although the laser power is significantly higher at QD GS energies, no CW THz signal was registered from PC antenna at these pump wavelengths, that perfectly agrees with the results previously demonstrated in the pulsed regime [25].

In order to obtain the THz signal, one wavelength of the pump laser was set to 1157.4 nm, which is just next to the photoconductance peak at 1157.3 nm, to ensure an efficient photocarriers generation. The stable dual-color laser operation with similar intensities for both wavelengths and with the second wavelength tuned to 1160.7 nm (corresponding to the difference frequency of 0.74 THz) and to 1161.1 nm (resulting in 0.83 THz) with total output power of double wavelength operation reaching 83 mW and 89 mW, correspondingly, was used for the demonstration of tunable THz generation in the QD PC antenna. The stable operation is extremely important for the efficient THz generation. No distinctive signal curve was detected at higher frequencies (above 1 THz). We attribute this absence partially to the relatively long lifetimes in the QD substrates and a large photoconductive gap (50 μm) between the electrodes. From our experiments in the pulsed regime [25], the signal at 1 THz was around 7 times less than at 0.74 THz. The measured THz signal data for both cases are shown in Fig. 5. The both THz signal dependencies on bias are easily fitted with quadratic trends, following the theoretical predictions [10]. The relatively higher signal at lower bias for the 0.83-THz curve might be associated with a higher pump power, and hence, a higher number of generated photocarriers. The efficient CW terahertz generation with a maximum output power of 0.6 nW was demonstrated at 0.83 THz with the pump QD laser operating in the dual-wavelength (1157.4 nm and 1161.1 nm) regime.

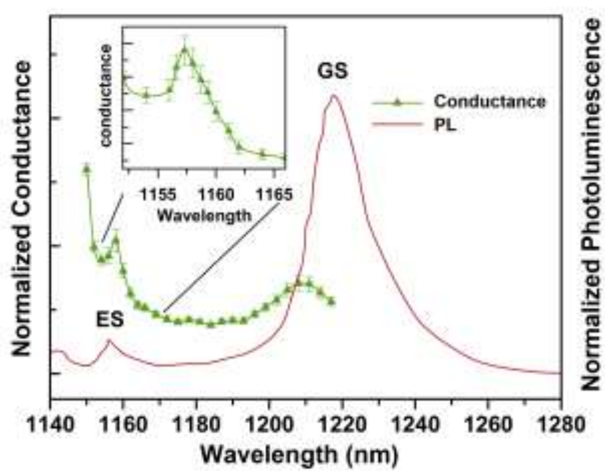

Fig. 4. The photoluminescence of the InAs/GaAs QD antenna wafer and the antenna photoconductance normalized to the pump laser power. The GS and the first ES of the QD wafer are indicated.

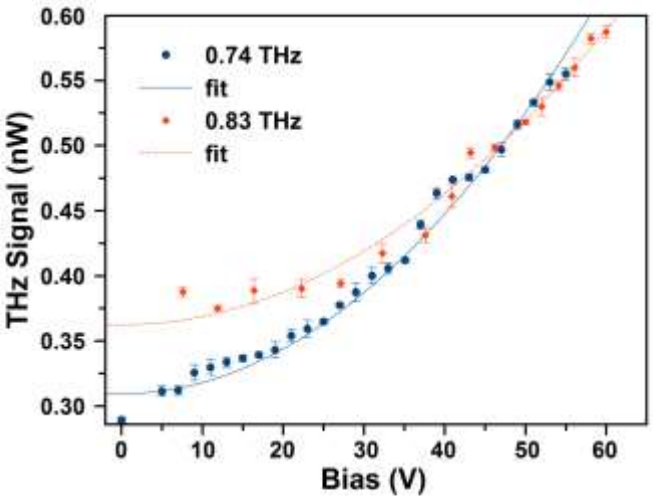

Fig. 5. The dependence of the measured THz signal intensity on bias antenna demonstrated from the all-quantum-dot laser source at 0.74THz and 0.83THz.

IV. Conclusion

In this work, we have demonstrated the generation of tunable efficient THz signal from a room-temperature all-semiconductor InAs/GaAs QD based setup, involving a QD based photomixer resonantly pumped by a compact, broadly-tunable dual-wavelength QD laser in the double-grating quasi-Littrow configuration. Such laser source emitting tunable THz radiation is of great interest for a number of applications, including indoor communications [27,28], biomedical imaging [29,30], spectroscopy [31,32], homeland security and defense [33,34], among others.

Further optimization of mutual designs of the both, QD laser and QD antenna wafer, for even more efficient conversion efficiency, and a comprehensive antenna electrodes design for better radiative properties at the frequencies of interest, as well as an inclusion of optical nanoantennas into the antenna gap [35], will result in significantly more power efficient operation and potentially will lead to the development of a practical, compact, sufficiently-powerful and reasonably-cheap, room-temperature tunable THz source.

Acknowledgment

The authors would like to thank Dr. D.A. Livshits and Dr. I. Krestnikov (Innolume GmbH) for the fabrication of the laser chip and the antenna, and Dr. R.R. Leyman (University of Strathclyde) for useful discussions.

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Ksenia A. Fedorova received the Ph.D. degree in Electronic Engineering and Physics from the University of Dundee, Dundee, U.K. in 2011. She is currently a research fellow at the Aston University in the Optoelectronics and Biomedical Photonics Group, where she is working on the study of novel quantum-dot materials for compact broadly tunable lasers and wavelength conversion using quantum-dot laser diodes and periodically poled nonlinear crystals. Her research interests also include the generation of mid-IR and THz radiation using novel quasi-phase-matched semiconductor nonlinear crystals.

Andrei Gorodetsky received his BSc an MSc degrees in physics from the Saint-Petersburg State University, St. Petersburg, Russia in 2003 and 2006, respectively, and the Ph.D. degree in optics from the ITMO University, St. Petersburg, Russia in 2010. Till 2011 he was with the Department of Photonics and Optical Informatics of the same University as a Senior Researcher and an Assistant Professor. From 2011 to 2013, he was a Postdoctoral Researcher in the Ultrashort Non-linear Interactions and Sources group at the Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, Heraklion, Greece, where he was engaged in THz metamaterial research and controlled THz generation in two-color plasma filaments. Since 2014 he is with the Optoelectronics and Biomedical Photonics group at the Aston Institute of Photonic Technologies, Aston University, Birmingham, UK. He is the laureate of Yu. I. Ostrovsky Prize for the best scientific work in the field of optical holography and interferometry in 2012. His current research interests include THz imaging, pump-probe THz studies and the development of quantum dot based compact THz sources.

Edik U. Rafailov received the Ph.D. degree from the Ioffe Institute in 1992. In 2005, he established a new group in the Dundee University and in 2014 he and his Optoelectronics and Biomedical Photonics Group moved to the Aston University, United Kingdom. He has authored and co-authored over 400 articles in refereed journals and conference proceedings, including two books (WILEY), five invited chapters and numerous invited talks.

Prof. Rafailov coordinated the €14.7M FP7 FAST-DOT project – development of new ultrafast lasers for Biophotonics applications. Currently, he coordinates the €11.8M NEWLED project which aims to develop a new generation of white LEDs. Recently he was awarded the H2020 FET project Mesa-Brain (€3.3M). He also leads a few others projects funded by EU FP7, H2020 and EPSRC (UK). His current research interests include high-power CW and ultrashort-pulse lasers; generation of UV/visible/IR/MIR and THz radiation, nanostructures; nonlinear and integrated optics; biophotonics.