Generation of phase-locked and tunable continuous-wave radiation in the terahertz regime

Qudsia Quraishi, Martin Griebel,* Thomas Kleine-Ostmann,† and Rudolf Bratschitsch‡

JILA, Department of Physics, University of Colorado and the National Institute of Standards and Technology, Boulder, Colorado 80309-0440

Received June 27, 2005; accepted July 25, 2005

Broadly tunable phase-stable single-frequency terahertz radiation is generated with an optical heterodyne photomixer. The photomixer is excited by two near-infrared CW diode lasers that are phase locked to the stabilized optical frequency comb of a femtosecond titanium:sapphire laser. The terahertz radiation emitted by the photomixer is downconverted into RF frequencies with a waveguide harmonic mixer and measurement-limited linewidths at the Hertz level are demonstrated. © 2005 Optical Society of America

OCIS codes: 320.7160, 140.2020, 190.4360.

Sources in the terahertz (THz) region have generated significant interest for their use in submillimeter wave THz applications, such as remote sensing, spectroscopy, and three-dimensional imaging. Much work has been done with THz pulses, including obtaining three-dimensional tomographic images by use of THz time-domain spectroscopy.[1,2] To facilitate high-resolution molecular spectroscopy, single-frequency THz generation has been achieved with molecular gas lasers.[3] Additionally, advances in THz receivers have generated a need for broadly tunable single-frequency local oscillators (LOs). Solid-state single-frequency THz generation has been demonstrated with optical heterodyne photomixers as well as with quantum cascade lasers (QCLs).[4,5] However, a source for broadly tunable, narrow linewidth, single-frequency THz radiation has thus far not been demonstrated. Here, we present the phase stabilization of two CW diode lasers to the stabilized frequency comb of a femtosecond titanium:sapphire (Ti:S) laser and generate, through optical heterodyne conversion in a photomixer, phase-stable CW THz radiation at the diode lasers' difference frequency. Using this stabilization scheme, we demonstrate the ability to obtain broadly tunable CW radiation in the THz regime and show that the frequency of this radiation is phase-stable with Hertz-level measurement-limited linewidths.

In recent years, developments in femtosecond lasers and the technologies for their stabilization have led to significant advances in the tools for spectroscopy, coherent control, and optical frequency synthesis.[6] The femtosecond Ti:S laser emits a discrete set of optical frequency lines spaced by the repetition rate f_{rep} of the laser. This frequency comb can be engineered to have excellent frequency stability resulting in a fixed, discretely spaced optical frequency ruler to which other lasers may be compared and stabilized.[7,8] In our work, we combine the powerful ideas behind stabilized optical frequency combs with the THz domain.

We phase-lock two external cavity diode lasers (DLs) to the stabilized frequency comb of the Ti:S lasers as shown in Fig. 1(a). The DLs are both centered near 850 nm and have optical powers of 100 mW (DL1) and 40 mW (DL2) (they are detuned from each other by the THz frequency, f_{THz}). We use a Ti:S laser with f_{rep} of 92.8 MHz, centered at 850 nm, with a FWHM bandwidth of approximately 65 nm and an output power of 400 mW. One optical beam splitter spatially overlaps the DL beams to generate the photomixer input, and a second beam splitter spatially overlaps the Ti:S laser beam with the DL beams [Fig. 1(a)]. The optical interference between each of the DLs and the frequency comb of the Ti:S laser is measured on a photodiode as heterodyne radio-frequency (RF) beat signals [Fig. 1(b)]. By locking the DLs to the comb of the Ti:S laser, we can dial in any frequency difference between the two DLs within the available bandwidth and tune this frequency by tuning the grating in the cavity of one DL.

Each DL is stabilized by locking the RF beat between the DL and the Ti:S laser using a phase-locked loop (PLL). We use a digital frequency-phase detector

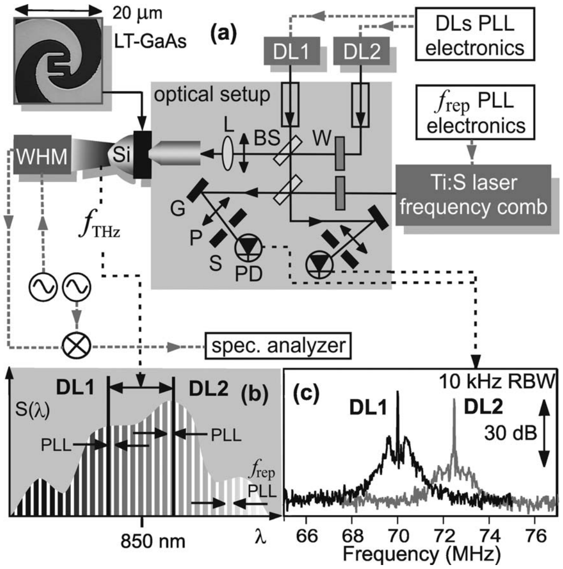

Fig. 1. (a) Configuration for phase locking of two CW diode lasers to the stabilized frequency comb of a femtosecond Ti:S laser. DL, diode laser; W, half waveplate; BS, 50/50 beam splitter; L, 50 cm lens; Si, silicon lens; WHM, waveguide harmonic mixer; G, grating; P, polarizer; S, slit; PD, photodiode. Inset, photo of the THz photomixer fabricated on LT-GaAs. (b) Schematic of the spectral output of two CW diode lasers and the Ti:S frequency comb. (c) Phase-locked beats (DL2 offset for clarity) between the diode lasers and the Ti:S laser.

0146-9592/05/233231-3/$15.00

to produce an error signal between the RF beat signal and a synthesized frequency that is used as a reference. The generated error signal is used in a feedback loop that adjusts the current of the diodes to control the optical frequency excursion. The locked beat note between each DL and the Ti:S laser displays a coherence spike indicating a phase lock [Fig. 1(c)]. The PLL performance is limited by the frequency response of the DLs to the error current inputs used to stabilize them (the bandwidth of the PLL is indicated by the servo bump in the noise pedestal at ~500 kHz).

To generate CW THz radiation at the difference frequency between the DLs, we optically heterodyne them on a photomixer.[9–12] The photomixer is a spiral, one and a half turn, gold antenna fabricated on low-temperature grown GaAs (LT-GaAs), with three interdigitated electrodes covering an area of 7 μm $\times 7$ μm and biased with 40 V [Fig. 1(a)]. The typical combined power on the photomixer is ~22 mW, and the spot size of the two beams covers the electrodes. The emitted THz radiation (f_{THz}) propagates through the LT-GaAs substrate, is coupled out of the substrate, and is then partially collimated by a hyper-hemispherical Si lens mounted in contact with the back of the LT-GaAs chip [Fig. 1(a)].[4]

We demonstrate broad tunablity, limited only by the available bandwidth of the photomixer, by tuning one of the DLs across the Ti:S frequency comb. For three settings of the optical separation between the DLs we use a waveguide harmonic mixer (WHM) to downconvert f_{THz} into RF frequencies. The WHM mixer allows for THz detection with response times that are orders of magnitude faster than the commonly used liquid helium cooled bolometers.[12] The THz radiation is coupled into the waveguide (RF port) of the harmonic mixer, which terminates at a Schottky diode. The Schottky diode generates harmonics when driven by a sythesized signal (LO port) and these mix the RF input to produce, at the intermediate frequency port, the difference frequency (<2 GHz) between f_{THz} and an LO harmonic.

The downconverted signal is subsequently amplified, mixed down into the sub-GHz regime (f_c) with a synthesized frequency and, finally, sent into a fast Fourier transform spectrum analyzer [Fig. 2(a)]. For the 0.303 THz (90, 40 GHz) signal we use for detection the WHM by Virginia Diodes WR-3.4HM (Agilent 11970W, Agilent 11970A [This information is given for technical purposes and does not represent an endorsement on the part of NIST.]). We have generated THz radiation up to the frequency cutoff (~1 THz) of the photomixer, using a bolometer for detection [Fig. 2(b)]. However, with the LO frequency range available to us, the conversion loss of the harmonic mixer did not allow for WHM detection at these f_{THz} frequencies. For both the 90 GHz and the 0.303 THz data shown in Fig. 2(a), bringing the signal above the noise floor required amplifiers. The RF signal levels give lower bound estimates on the power, coupled into the waveguide, of f_{THz} emitted from the photomixer from the known conversion loss of each of the WHMs. We estimate for the 0.303 THz (90, 40 GHz) signal with a conversion loss of 35 dB (46, 26 dB) to have coupled 1 nW (10, 6 nW) of power. No efforts were made to focus the radiation into the waveguide, and thus the total power emitted from the photomixer may be larger than the power coupled into the WHM. For the downconverted and amplified 40 GHz signal, there was a sufficient signal-to-noise ratio in a 10 kHz resolution bandwidth (RBW), as shown in Fig. 2(c), to record linewidth characteristics similar to those observed in Fig. 1(c).

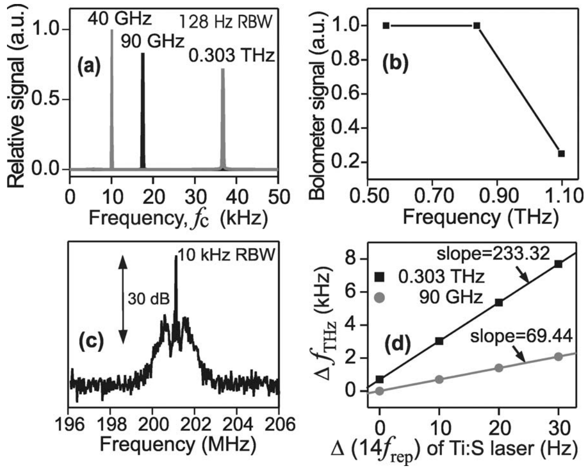

Fig. 2. (a) f_{THz} from the photomixer at 0.303 THz (90, 40 GHz), downconverted with the 18th (16th, 8th) harmonic of a synthesized signal at 16.72 GHz (5.6, 5 GHz) in a waveguide harmonic mixer then mixed down into the kHz regime (shifted for clarity). [The typical SNR in a 100 kHz RBW is 7 dB (8, 15 dB) at 0.303 THz (90, 40 GHz).] (b) Bolometer-detected f_{THz} signal, showing THz generation up to 1.1 THz. (c) Phase-locked 40 GHz signal downconverted, displaying linewidth characteristics similar to those observed in Fig. 1(c). (d) Frequency scan of f_{THz} obtained by incrementing the frequency of the synthesized signal phase locking the 14th harmonic of the Ti:S f_{rep} (offset for clarity).

To obtain phase-stable f_{THz} radiation, we stabilize the difference frequency between the two DLs by phase locking the 14th harmonic of f_{rep} to a synthesized frequency. One cavity mirror in the Ti:S laser is mounted on an actuator and is used for f_{rep} stabilization. By scanning f_{rep}, as shown in Fig. 2(d), we can readily obtain continuous f_{THz} tuning of tens of MHz, which would be useful for rapidly scanning a molecular absorption line. The center value about which f_{rep} was scanned was 1.29851 GHz, corresponding to 3266 (972) Ti:S comb lines between the two DLs and yielding a frequency of f_{THz} of approximately 0.30297 THz(90.17 GHz) (a wavemeter measurement confirmed the frequency difference between the DLs). Indeed, a very useful feature of phase locking to a frequency comb is the possibility of achieving broad *continuous* tunability of the DLs' difference frequency over many THz by tuning one (or both) of the DLs across the frequency comb [Fig. 1(b)].[7]

Another advantage of phase locking the DLs to the comb of the femtosecond laser for THz generation with a photomixer is the ability to obtain very narrow linewidth THz radiation. The linewidths of the 0.303 THz and 90 GHz signals, for an acquisition time of 1 s, reveal measurement-limited linewidths at and below the Hertz level, respectively [Fig. 3(a)]. The detection scheme does not add appreciable noise, and so the mixed-down signal contains the noise properties of f_{THz}. The sidebands at harmonics of 85 Hz for the 0.303 THz signal are larger than those for both the 90 GHz [Fig. 3(a), inset] and the 40 GHz (not shown) signal, and may be attributed to noise on f_{THz} arising from mechanical resonances associated with the actuator used to stabilize f_{rep}. In comparison, the free-running linewidth of a QCL operating at 4.7 THz was reported to be 31 kHz at a 3 ms sweep time.[13]

The relative noise on f_{THz} is expected to increase as the number of frequency comb lines between the DLs is increased.[14] This occurs because with larger separations between the DLs, the dominant contribution to the noise arises from the phase noise of the quartz crystal oscillator used as a microwave reference (f_m) to lock f_{rep}. Indeed, the noise on the signal scales as expected ($20 \log f_{\mathrm{THz}}/f_m$) with the THz frequency [Fig. 3(b)]. The data presented here [Fig. 3(b)] lead us to expect significant coherence to be evident for the data presented in Fig. 2(b).

In conclusion, we have demonstrated an all-solid-state system generating phase-stable and tunable CW THz radiation at the difference frequency of two diode lasers individually phase locked to the stabilized optical frequency comb of a Ti:S laser. We downconverted the radiation into RF frequencies and demonstrated measurement-limited linewidths at the Hertz level. This stabilization scheme has the potential to be made physically compact and to provide access to any frequency difference between the DLs, from DC to hundreds of THz, that is both phase-locked and broadly tunable. In addition, the frequency comb can readily be referenced to an atomic standard, yielding an accuracy of 1 part in 10^{12}, for absolute THz frequency measurements. These results are also significant for advancing techniques in precision molecular spectroscopy.

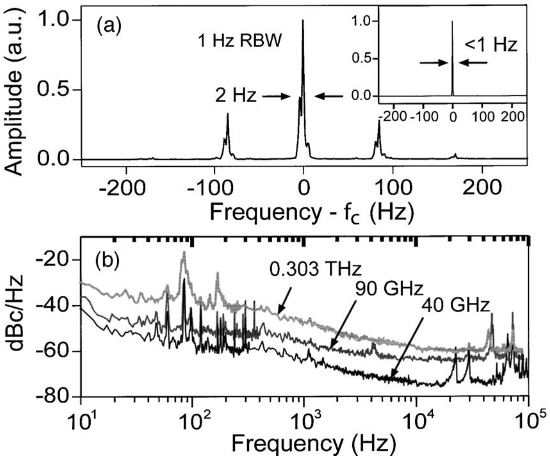

Fig. 3. (a) f_{THz} radiation at 0.303 THz at a 1 Hz RBW demonstrating a measurement-limited linewidth at the Hertz level, where $f_c = 14$ kHz. Inset, linewidth below the measurement 1 Hz RBW for the 90 GHz signal, where $f_c = 12$ kHz. (b) Relative phase and amplitude noise of the CW radiation at 0.303 THz, 90 GHz, and 40 GHz. The traces scale with the phase noise of the quartz crystal oscillator locking f_{rep}. These noise traces were obtained by downconverting the phase-locked f_{THz} radiation with a WHM, then mixing down to f_c, where f_c is set at approximately 10 kHz for each f_{THz}.

We gratefully acknowledge technical contributions from D. Alchenberger, T. Brown, M. Notcutt, R. Mirin, and J. Hesler. S. Cundiff suggested the Ti:S laser for CW THz generation. We thank J. L. Hall and L. W. Hollberg for valuable discussions. Funding was provided by NIST, the National Science Foundation (grant PH0096822), and the Department of Physics of the University of Colorado. Correspondence should be directed to quraishi@colorado.edu.

Note added in proof: Recently, a 3 THz QCL was locked to a far-infrared gas laser with a linewidth of 65 kHz in a 1 kHz RBW.[15]

*Present address, Heinrich-Heine-Strasse 18/3, 72555 Metzingen, Germany.

†Present address, Institut für Hochfrequenztechnik, Technische Universität Braunschweig, Schleinitzstrasse 22 38106 Braunschweig, Germany.

‡Present address, Fachbereich Physik, LS Leitenstorfer, University of Konstanz and Center for Applied Photonics, 78457 Konstanz, Germany.

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