Tunable telecom MEMS-VCSEL for wideband terahertz photomixing

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***Abstract*—We report terahertz generation with photomixers that are driven by an ultra-broadband tunable micro electro-mechanical system (MEMS) vertical-cavity surface-emitting laser (VCSEL) and a fixed-wavelength VCSEL. Electro-thermal tuning of the MEMS-VCSEL enables wideband terahertz photomixing. A frequency span of 3.37 THz is covered which is solely limited by the dynamic range of the terahertz components.**

I. INTRODUCTION AND BACKGROUND

TERAHERTZ (THz) science and technology is an emerging research field due to various potential applications [1]. The large availability of optical components around 1550 nm facilitates the inexpensive generation of THz radiation compared to established 850 nm systems. Suitable photomixers can convert the difference frequency of two heterodyned laser beams at frequencies ν_1 and $\nu_2 = \nu_1 + \nu_{\mathrm{THz}}$ into an AC current. The RF signal then can be fed into an antenna in order to generate THz radiation. The main limitation for telecom devices, however, is the limited tuning range of inexpensive distributed feed back (DFB) laser diodes that are mostly used as laser sources. In contrast to conventional edge-emitting lasers (EELs), VCSELs have vertical cavities and emit light perpendicular to the wafer surface. In order to incorporate a tuning mechanism, one of the two laser mirrors has to be replaced by a movable mirror. We fabricate MEMS movable DBR (distributed Bragg reflector) on top of a half-VCSEL structure (containing the bottom fixed-DBR) [2], together incorporating a resonator length of few micrometers. Of this resonator, the air-gap L_{air} between the MEMS-DBR and the half-VCSEL can be tuned by means of electro-thermal actuation of the MEMS. The free spectral range (FSR) is of the order of 10 THz. An ultra-broadband tuning over the entire FSR is possible. Therefore, a MEMS-VCSEL-based photonic system can cover the whole THz range with a single pair of compact semiconductor lasers. In this work, we report tunable THz signal generation from -1.64 THz to $+1.73$ THz, i.e. a total frequency span of 3.37 THz.

II. MEMS-VCSEL CHARACTERISTICS

Electro-thermal tuning is realized by actuating the heating-electrode of the MEMS-DBR. The generated heat P_{heat} thermally expands the DBR resulting in increase of the resonator length (or resonance wavelength). With further increase of the P_{heat}, continuous wave (CW) tuning of the emission peak is achieved. P_{heat} is, therefore, proportional to the square of the tuning-current I_{mems} and the emission wavelength λ according to $\Delta\lambda \propto \Delta L_{\mathrm{air}} \propto P_{\mathrm{heat}} = I^2_{\mathrm{mems}} \cdot R$, where R is the electrical resistance of heating-electrode. The complete CW-tuning over 76 nm of the MEMS-VCSEL used in this experiment is demonstrated in Fig. 1. An even larger tunability of 102 nm (approx. 13 THz) has already been reported in ref. [2]. We also investigate the electro-thermal frequency response of the MEMS-VCSEL for a sinusoidal modulated tuning-current. It shows a first-order low pass characteristics with a cut-off frequency of $f_{3dB} = 200$ Hz. At high frequencies, the tuning range falls off 10 dB/decade, stemming from the fact that the finite thermal response of the MEMS-DBR (thermal time constant of 1.3 ms) hinders to follow the fast modulation tuning-current. However, still using a periodic tuning-current of frequency less than f_{3dB}, a fast THz detuning with respect to another laser can be realized by a MEMS-VCSEL. However, as MEMS-DBR is suspended over the half-VCSEL, it is not immune to external disturbances such as vibrations. As a result, wavelength fluctuations can be observed, necessitating stabilization techniques at each tuned point. We develop a control circuit for this purpose where a commercially available telecom wavelength locker (WL) module provides the control variables. A fraction of the total laser power is given to the WL as input which is internally splitted into two branches. One of these branches is first fed to an etalon, followed by

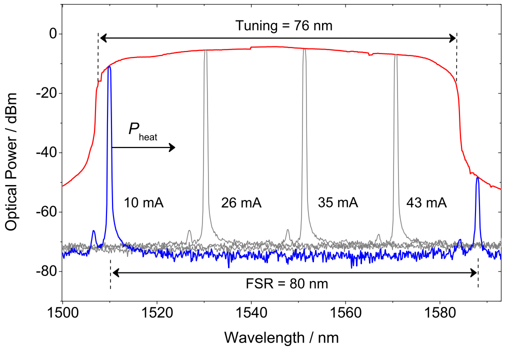

Fig. 1. The MEMS-VCSEL features a mode-hop free CW-tuning range of 76 nm (corresponding to 9.5 THz). The tuning range is given as the envelope of the fundamental laser peak emission while tuning. Few single emission spectra at different tuning-currents are shown to clarify CW-tuning with single-mode emission.

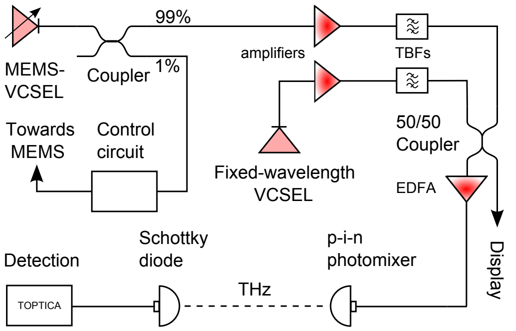

Fig. 2. Tunable CW THz-photomixing set-up using two VCSELs.

a p-i-n photodiode (PD). Fabry-Perot periodic oscillations with respect to the frequency of 100 GHz ($\sim$0.8 nm) FSR in the etalon lead to same periodic oscillations of the PD electrical current, I_{etalon}. For a frequency at the rising or falling edge of a Fabry-Perot peak, the etalon response is steep and linear with respect to small frequency variations. This signal is used for locking. In order to exclude power variations of the signal, it is normalized to the reference signal from the second branch that is directly delivered to a reference p-i-n PD for power monitoring. In the experiment, the wavelength is locked to the positive slope of the etalon's transmission function where $I_{\mathrm{etalon}} = I_{\mathrm{ref}}$. A normalized error voltage after a logarithmic transimpedance amplifier as $V_{\mathrm{err}} = (1V) \cdot \log\left(I_{\mathrm{etalon}}/I_{\mathrm{ref}}\right)$ is given as negative feedback to the main tuning current of the MEMS-DBR counteracting any unwanted change of wavelengths by rapid increase/decrease of the tuning current. In order to alter the locking wavelength, a comparator circuit tracks the periodic V_{err} with increasing current. Once a lock-point is tracked while tuning, only then feedback is added to stabilize the MEMS-VCSEL. The locking and tuning are accomplished automatically using a microcontroller-enabled program.

III. EXPERIMENTAL SET-UP AND RESULTS

The experimental set-up is illustrated in Fig. 2. 1% power of the MEMS-VCSEL is tapped out for the control and sweep circuit. Both VCSELs are amplified by separate Erbium-doped fiber amplifiers (EDFAs). Tunable band-pass filter (TBF) remove the amplified spontaneous emission (ASE) noise resulting in a clean THz signal. However, the TBF after the fixed-wavelength VCSEL does not need to be a tunable one, an alternative low-cost fixed-wavelength filter can be used instead. The VCSEL outputs are finally combined by an optical 50/50 coupler. The combined output signal is further amplified to attain much better signal-to-noise ratio (SNR) and finally it pumps the p-i-n photomixer for THz generation. The 3 - dB bandwidths of both filters are set to 200 pm during the experiment. A zero-bias Schottky diode is used on the detection side. A commercial CW TOPTICA setup enables lock-in detection with 600 ms integration time of the received THz-photocurrent. The lock-in detection is enabled by bias-modulation of the p-i-n photomixer. This THz setup can follow a frequency tuning up to 1.75 THz which is limited by the dynamic range of the used emitter-receiver pair. In order to demonstrate the wideband tuning capability of the MEMS-VCSEL, the difference-wavelength is tuned by WL-circuit from $\lambda = 1535$ nm up to $\lambda = 1562$ nm with respect to the fixed-VCSEL at $\lambda = 1548$ nm. This corresponds to 27 nm or 3.37 THz electro-thermal tuning. The full tuning of 76 nm of this MEMS-VCSEL, however, is demonstrated in Fig. 1. A single MEMS-VCSEL combined with a fixed-wavelength laser can therefore be used to cover most of the THz range with a single optical set-up. The corresponding THz-signal detection against the absolute difference-frequency is plotted in Fig. 3. The roll-off of the detected THz-signal is due to the roll-off of the p-i-n emitter $\left(\sim \nu^2 - \nu^4\right)$ [3] and the roll-off of the Schottky diode $\left(\sim \nu^2\right)$ [4] that are used for detection. The further tuning capability of this setup, as stated above, is solely limited by the dynamic range of the THz emitter/receiver system.

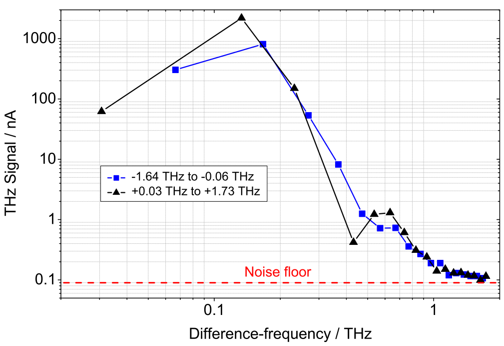

Fig. 3. Detected THz-signal vs. absolute difference-frequency. The difference-frequency is tuned from -1.64 THz to -0.066 THz (squares) and from $+0.03$ THz to $+1.73$ THz (triangles).

IV. CONCLUSION

We demonstrate an ultra-broadband VCSEL-based laser system for driving THz photomixers, where one of the VCSELs employs a MEMS movable DBR for frequency tuning. The tuning range of the MEMS-VCSEL is 9.5 THz, yet much larger than the bandwidth of the used THz components. The full tuning range of the MEMS-VCSEL can be deployed with improved THz emitter and detector concepts.

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REFERENCES

[1] M. Tonouchi, "Cutting-edge terahertz technology," *Nature Photon.*, vol. 1, pp. 97−105, 2007.

[2] C. Gierl et al., "Surface micromachined tunable 1.55 μm-VCSEL with 102 nm continuous single-mode tuning," *Opt. Express*, vol. 19, pp. 17336−17343, 2011.

[3] S. Preu et al., "Tunable, continuous-wave Terahertz photomixer sources and applications," *J. Appl. Phys.*, 109, 061301, 2011.

[4] A. Semenov et al., "Application of zero-bias quasi-optical Schottky-diode detectors for monitoring short-pulse and weak terahertz radiation," *IEEE Electron Device Lett.*, vol. 31, pp. 674−676, 2010.