Ultra-Broadband Telecom MEMS-VCSEL for Frequency-Tunable Terahertz Generation with Photomixers

M. T. Haidar[1], S. Paul[1], C. Gierl[1], S. Preu[2], and F. Küppers[1]
[1]Institute for Microwave Engineering and Photonics, Technische Universität Darmstadt, Merckstr. 25, 64283, Darmstadt, Germany

[2]Terahertz Systems Technology, Dept. of Electrical Engineering and Information Technology, Technische Universität Darmstadt, Merckstr. 25, 64283, Darmstadt, Germany

***Abstract*—We report on all-fiber tunable terahertz (THz) signal generation based on a tunable Micro Electro-Mechanical System Vertical-Cavity Surface-Emitting Laser (MEMS-VCSEL) and a fixed wavelength VCSEL. The VCSELs pump a n-i-pn-i-p supperlattice broadband photomixer. Signals between 33 GHz and 690 GHz were successfully generated, with no fundamental limit towards larger tuning ranges.**

I. INTRODUCTION

Telecommunication data rates and required bandwidth are exponentially increasing. Especially in the wireless communication systems, new bands at higher frequency ranges such as the THz-range have to be used in order to keep pace with the increasing amount of traffic [1]. At the front end, an ultra-fast diode is required to down-convert the optically transmitted signal to an electrical one. Telecom-wavelength compatible THz photomixers represent an ideal optical-to-RF converter for this purpose. Photomixers convert the difference frequency of two heterodyned laser beams at frequencies ν_1 and $\nu_2 = \nu_1 + \nu_{THz}$ into an AC current. They can also down-convert a high frequency signal that is modulated on a single laser. The RF signal can either directly be used in high frequency circuits or be fed into an antenna in order to generate THz radiation.

Besides telecommunications, photomixers are used in many THz applications. Such applications benefit from the inexpensive optical components if 1550 nm photomixers can be used instead of the established 800 nm systems.

A main limitation for telecom devices, however, is the limited tuning range of inexpensive DFB laser diodes that are mostly used as laser sources. In contrast to the conventional edge-emitting lasers (EELs), VCSELs have a vertical cavity (normal to the wafer surface) and therefore emit light from the top. The very short optical cavity (few micrometers) implies very large free spectral range (FSR) of the VCSEL, which in turn enables highly single mode emission with a large mode hop free tuning range.

In this work, we report on an all-fiber tunable THz-source using two telecom wavelength VCSELs, and a n-i-pn-i-p superlattice photomixer with a broadband antenna to generate THz radiation. Of these two VCSELs, one is an in-house fabricated electro-thermally tuned MEMS-VCSEL [2]. The other VCSEL is a commercial telecom VCSEL operated at a fixed wavelength.

II. EXPERIMENTAL SET UP

Fig. 1 shows the experimental setup. The VCSEL outputs are combined by an optical 50/50 coupler. The coupled optical power is then amplified by an Erbium-doped fiber amplifier (EDFA). One of the laser outputs (the tunable one) is chopped by a mechanical chopper before the 50/50 optical coupler in order to enable the lock-in detection. The difference wavelength was tuned by electro-thermal tuning (MEMS current) of the MEMS of the VCSEL.

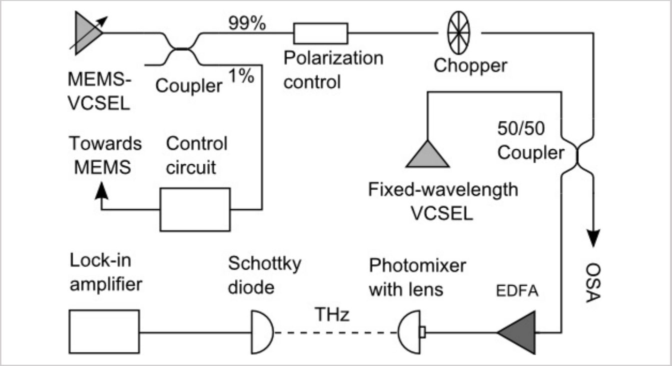

Fig. 1. Experimental set-up for tunable continuous-wave (CW) THz generation using two VCSELs.

The MEMS-VCSEL is wavelength stabilized in order to compensate for any fluctuation of MEMS. Such fluctuations change the optical path length in the cavity, $\Delta L = \frac{m\Delta\lambda}{2}$, where $\Delta\lambda$ is the resulting shift of the emission wavelength and m is an integer representing the order of the longitudinal mode.

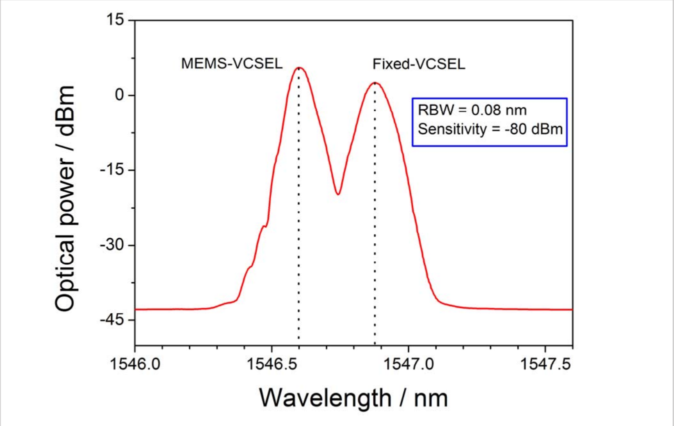

Fig. 2. Coupled optical spectrum of two VCSELs, the MEMS-VCSEL is wavelength stabilized.

A broadband Fabry-Pérot wavelength locker is the main part of this locking mechanism. The wavelength locker consists of a reference pin-photodiode and an etalon-coupled pin-photodiode. 1% of the optical power from the MEMS-VCSEL is tapped out by an optical coupler and then fed to the wavelength locker. The current from these photodiodes are given to a transimpedance amplifier which provides a normalized voltage output. This voltage is manipulated to provide positive/negative feedback to the MEMS-current. A microcontroller is used to manifest the automatic wavelength switching of MEMS-VCSEL. Figure 2 shows the optical output from the two VCSELs at a difference frequency of 33 GHz (λ_{MEMS} = 1546.598 nm and λ_{fixed} = 1546.875 nm. The MEMS-VCSEL is wavelength stabilized and maximum hold detection mode of the optical spectrum analyzer (OSA) shows no changes in wavelength of the MEMS-VCSEL within an observation period of five hours.

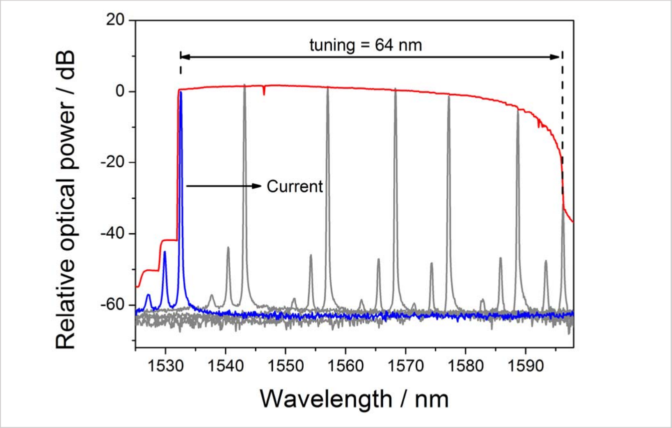

Fig. 3. Emission spectra of a thermally tuned MEMS-VCSEL, a tuning of 64 nm is shown by the envelope of the fundamental laser peak (red). Emission at 0 mA (blue) and several higher tuning currents of up to 27 mA (grey) are also shown.

III. RESULTS

A record electro-thermal tuning of 102 nm (electrically pumped VCSEL) has been reported for MEMS-VCSEL [2]. Fig. 3 shows the emission spectra of the tunable MEMS-VCSEL used for this experiment. The MEMS-VCSEL is tuned continuously over 64 nm by tuning the heating current of the MEMS (I_{tuning} = 0 mA – 27 mA), indicated by the grey graphs. It can be tuned further until the next longitudinal mode appears on the left which is not shown in Fig. 3. However, the generation of a 1-THz signal requires a wavelength tuning of around 8 nm (with respect to the fixed-wavelength VCSEL) according to $\Delta\upsilon = \frac{\Delta\lambda . c}{\lambda^2}$, where $\Delta\upsilon$ and $\Delta\lambda$ is the offset in frequency and wavelength, respectively, c is the speed of light in optical medium, and λ is the fixed wavelength. In this work the difference wavelength is tuned over a range from 0.87 nm to 5.45 nm, corresponding to a difference frequency tuning from 109.38 GHz to 685.15 GHz. There is no fundamental limit in terms of further tuning.

Fig. 4 shows the detected THz signal against the beat-frequency. The noise floor of 0.0016 mV (equivalent to -58 dB) of the lock-in amplifier is also plotted. The roll-off of the detected THz signal is due to the roll-off of the n-i-pn-i-p superlattice emitter ($\sim\nu^2$) [3] and the roll-off of the Schottky diode ($\sim\nu^2$) [4] that was used for detection.

Fig. 5 shows the beat-signal for a difference frequency of the two VCSELs of 33 GHz, measured with a fast photodiode attached to an electrical spectrum analyzer (ESA). The corresponding optical spectrum is shown in Fig. 2. The Gaussian-fit of this spectrum approximates a 452 MHz line-width of the beat signal.

IV. SUMMARY

We have generated a tunable THz signal up to 690 GHz using two VCSELs. In our future work, we aim to generate and detect a THz-signal up to several THz. However, this requires a THz-system with larger-bandwidth and dynamic range (for example, higher photomixer bandwidth). We also aim to fabricate tunable MEMS-VCSEL and fixed wavelength VCSEL in pair in monolithic fabrication process. These VCSEL pairs can be incorporated into an integrated, miniaturized THz system.

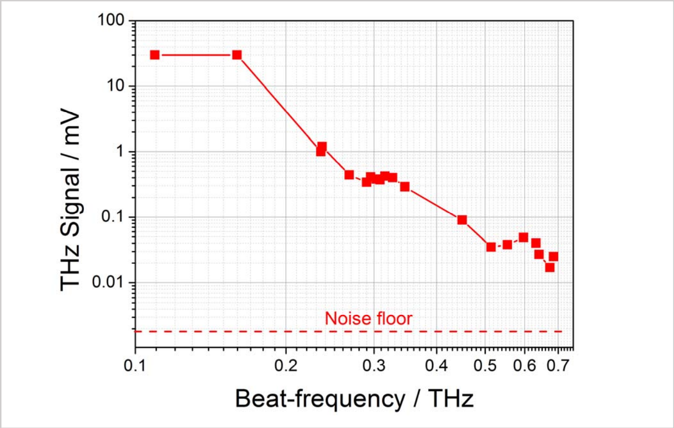

Fig. 4. Detected Terahertz (THz) power vs frequency in a log-log scale

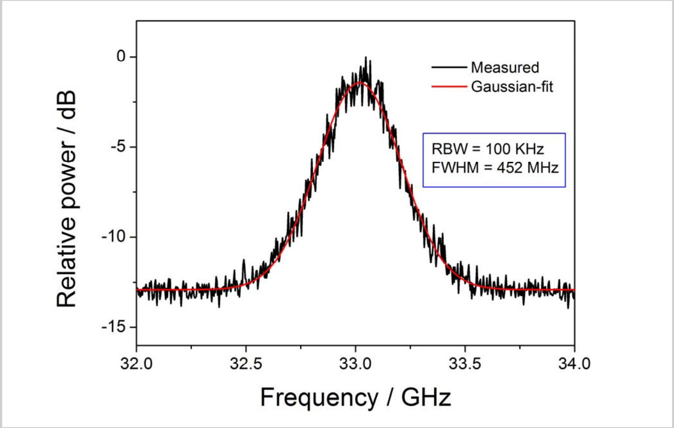

Fig. 5. Beat-signal detection by ESA. The corresponding Gaussian-fit shows a full-width-half-maximum (FWHM) of 452 MHz.

REFERENCES

[1]. S. Koenig et al. "Wireless sub-THz communication system with high data rate," *Nature Phot.,* 7, 977-981, (2013).

[2]. C. Gierl et al. "Surface micromachined tunable 1550 nm-VCSEL with 102 nm continuous single-mode tuning," *Opt. Express*, Vol. 19 (18), 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, 0741-3106, (2010).