Progress Towards an Ultracompact cw Terahertz Spectrometer

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***Abstract*— A cw terahertz spectrometer operating without optical amplifiers and without mechanical delay line is presented. Fiber-coupled 1.5 µm DFB lasers in a "butterfly" housing drive a photodiode emitter, which provides 5 µW output at 0.5 THz. A coherent photoconductive receiver yields an SNR up to 75 dB.**

I. INTRODUCTION

A significant advantage of continuous wave (cw) terahertz systems is the simplicity of the optical source. This is especially the case if telecom-qualified lasers at 1.5 µm can be used. Here, distributed feedback (DFB) diodes with high output power are available in fiber-coupled "butterfly" modules. However, there has been a lack of cw terahertz emitter and coherent receiver modules. The first cw terahertz spectrometers were thus based on GaAs photomixer devices, requiring a laser wavelength around 800 nm. Superior signal-to-noise ratios (SNR) and a wide bandwidth were demonstrated [1, 2], yet non-standard optical components drive the costs of these systems.

Recently, InGaAs/InGaAsP photodiode emitters and InGaAs/InAlAs photoconductive receivers were developed for 1.5 µm operation [3, 4]. In this work we merge the advantages of state-of-the-art DFB lasers at 1.5 µm and the emitter / coherent receiver concept outlined in [4] into an ultra-compact, high performance and low cost cw terahertz spectrometer.

II. SYSTEM DESIGN

Our setup comprised two DFB lasers with center wavelengths of 1537 nm ("laser 1") and 1535 nm ("laser 2"). We used off-the-shelf butterfly packages with built-in thermo-electric cooler (TEC), optical isolator and polarization-maintaining fiber pigtail. The fiber output power was 50 mW per laser, and both lasers were packaged, together with an additional in-line fiber isolator each, in a small metal box (15 cm x 10 cm x 5 cm). In contrast to previous work [2, 4], no semiconductor or fiber amplifiers were used in this system. The output of the laser diodes was connected to a 2x2 fiber array to combine the two wavelengths, and to illuminate the terahertz emitter and receiver.

Calibration curves for both lasers (wavelength vs. temperature) were recorded, using a precise wavelength meter (HighFinesse Ångstrom WS6-IR1). These calibration curves (Fig. 1) were stored in a look-up table, which then served to select the appropriate temperature settings for any desired terahertz frequency. A digital interface unit ("TeraControl 110", Toptica Photonics) converted the temperature settings into analog control voltages, achieving an absolute accuracy of the difference frequency of ~ 1 GHz and a resolution of < 5 MHz.

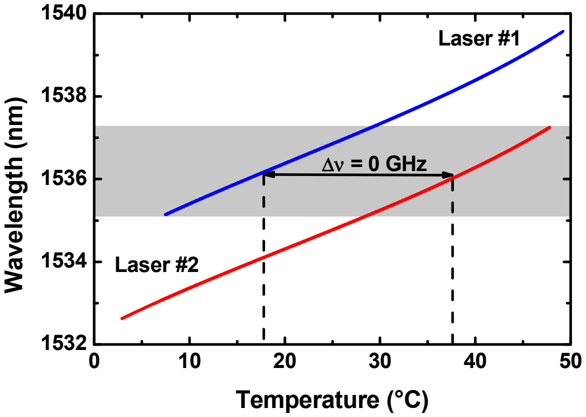

Figure 1: Wavelength calibration curves. The emission wavelength of the DFB lasers was thermally tuned. Equal wavelengths were reached at temperature settings of 18 °C and 37.5 °C for laser 1 and 2, respectively. The maximum difference frequency amounted to 885 GHz.

A waveguide-integrated photodiode antenna (WIN-PDA) with bow-tie structure was used as terahertz emitter. The advantage the waveguide design is a long coupling region (20 µm) of the evanescent light wave, and consequently a high efficiency even for thin absorbing layers (e.g. 300 nm). In order to optimize the coupling from the optical fiber into the waveguide structure, we integrated a tapered section into the waveguide at the fiber-chip interface. The WIN-PDAs were not packaged, but centered on a test platform with an inserted silicon lens. The optical fiber was adjusted to the tapered waveguide using piezo controllers.

A LT-InGaAs/InAlAs photoconductive receiver [3] served as coherent detector. In a multi-layer structure, 100 periods of Beryllium-compensated, 12 nm thin LT-InGaAs layers were embedded between InAlAs trapping layers. A 90 degree bow-tie design was chosen for the antenna, matching the structure of the bow-tie emitter. The receiver chips were packaged into fiber-coupled modules.

The terahertz signal generated by the WIN-PDA was guided through two polyethylene lenses to the receiver module. Bias modulation of the emitter (0 / −2.2 V, 30 kHz), and lock-in detection of the receiver signal were accomplished by the TeraControl unit.

Fig. 2 sketches the setup of the spectrometer and depicts its key components.

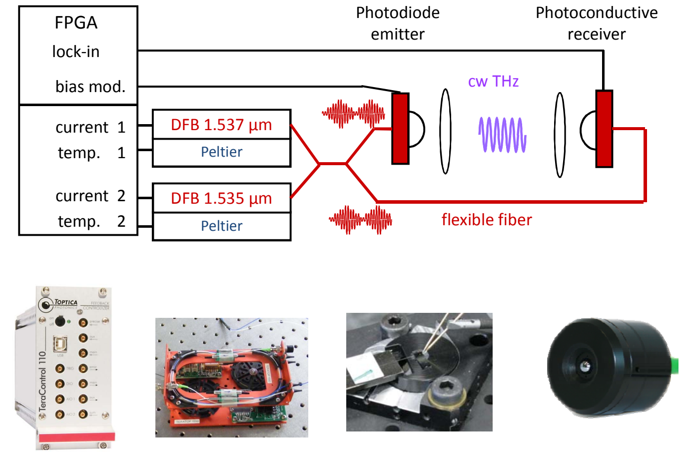

Figure 2: Top: schematic setup of the 1550 nm cw terahertz system; bottom: photos of the key components. From left to right: Digital control unit, laser assembly, photodiode emitter, packaged receiver module.

III. RESULTS

The radiation emitted by the WIN-PDA was measured using a factory calibrated Golay cell (Tydex, model GC-1P). A maximum terahertz output power of about 5 µW at 0.5 THz was achieved at a laser power of 25 mW (Fig. 3). The terahertz power is thus more than a decade higher than values reported for GaAs photoconductive antennas with comparable optical input power at similar frequencies [1].

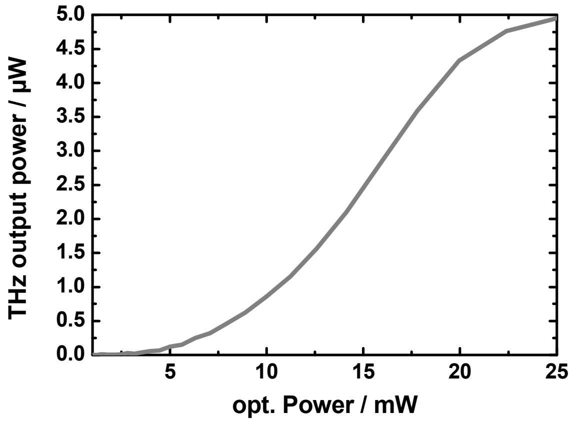

Figure 3: Terahertz power vs. optical input power, of a WIN-PDA emitter with 100 µm bowtie antenna.

Terahertz signals were recorded from 50 to 885 GHz, at a moderate optical power of 25 mW per two-color fiber output. The terahertz frequency was varied in steps of 30 MHz. No delay line was needed; rather, the terahertz phase was varied by changing the frequency in small steps in a manner outlined in [2]. The resulting photocurrent was preamplified by a factor of 10^6 and measured with a lock-in integration time of 300 ms per frequency point. Results are summarized in Fig. 4, where the SNR is extracted from the envelope of the phase oscillations of the receiver photocurrent.

The SNR of the terahertz power was computed via

$$\mathrm{SNR} = 20 \text{ x } \log (I_{\mathrm{Signal}} / I_{\mathrm{Noise}}),$$

where I_{Signal} is the measured receiver photocurrent, and I_{Noise} denotes the noise current measured with a blocked beam. The SNR amounted to approx. 75 dB @ 125 GHz, and still > 40 dB @ 800 GHz.

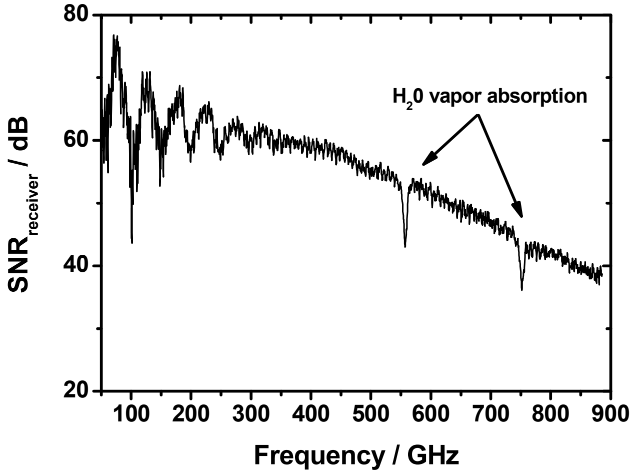

Figure 4: SNR spectrum. The frequency step width was 30 MHz; analyzing the envelope of the phase oscillation yields an effective resolution of ~ 180 MHz.

We note that the difference frequency range of these DFB lasers was limited to ~ 900 GHz because of the large overlap region of the tuning range of nearly 2 nm (grey region in Fig. 1). This can be enhanced by selecting two DFB lasers with a larger wavelength offset. If both laser wavelengths overlapped at the extreme ends of the temperature spectrum, the difference frequency range would broaden to ~ 1.2 THz. By using a third laser with a further wavelength offset an even broader tuning range can be envisaged, e.g. from 1 THz to 2.2 THz.

The simplified optical source combined with fiber coupled transmitter and receiver modules paves the way to highly compact, flexible, and cost-effective cw THz spectrometers.

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