Continuous-Wave Electro-Optic Terahertz Dual-Comb Operating from 0.096 to 0.496 THz Using ErAs:In(Al)GaAs Photoconductors

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***Abstract*— An absolute-frequency terahertz (THz) dual-comb system was implemented using only standard telecom components, such as continuous-wave (CW) single mode lasers, optical modulators, and erbium-doped fiber amplifiers (EDFAs) for driving a pair of ErAs:In(Al)GaAs photoconductors. The dual-comb center frequency was tuned between 0.09596 and 0.49596 THz while the mode spacing was kept at 0.5 GHz, although any other lower frequency was also possible.**

I. INTRODUCTION

SINCE its inception, THz dual-comb spectroscopy has attracted a lot of attention within the THz community due to its large bandwidth coverage and rapid acquisition schemes, allowing to distinguish vibrational and rotational transitions with narrow spectral features in the 0.1-3 THz region in just a few seconds. Pulsed THz dual combs are fairly complex and expensive, involving either two locked ultra-short pulsed lasers with a slight offset in their repetition rates [1] or one ultra-short pulsed laser emitting at two slightly different wavelengths but with a slight offset between their repetition rates [2]. The complexity of the system is further increased when a resolution below the repetition rate is required, since the latter parameter then needs to be adjustable in at least one of the pulsed lasers [3]. Those complex schemes lack modularity, and hinder applications other than laboratory-scale spectroscopy. Furthermore, for applications like sub-THz communication absolute and tunable frequency resolution as well as CW operation are more important than wide THz bandwidth. In this paper, we present a modular THz dual-comb system based on electro-optical modulation of CW telecom lasers, and subsequent THz down-conversion by photomixers. The architecture of the system is an alternative version of the one presented in [4], and in particular in [5]. In this paper, however, all photomixers are EraAs:In(Al)GaAs photoconductors used in multi-heterodyne detection scheme. Unlike pulsed THz dual-comb architectures, this system architecture allows to change the THz comb repetition rate, and hence the frequency resolution, by simply tuning the frequency of a RF generator. This, in addition to its modularity and reduced complexity, makes the system well suited as a non-destructive testing platform or as a testbed for sub-THz communication.

II. SYSTEM ARCHITECTURE

Fig. 1 shows a schematic diagram of the THz dual-comb architecture. The starting point is the generation of an optical frequency comb, henceforth master comb, by modulating the output of a single mode laser, henceforth master laser (ML). The modulation is performed by two cascaded electro-optical phase modulators (EOMs) driven by an RF generator with frequency f_{MAST}. Since the RF signal driving the EOMs has to be phased-matched for an optimal generation, an RF tunable delay line is added before one of the EOMs. The optical comb generation is achieved by sinusoidal phase modulation of the CW laser signal. The optical field $E_{opt}(t)$ after the modulation can be expressed as

$$E_{opt}(t) = E_0 e^{j(\omega t + K sin(\omega_{MAST} t))} \qquad (1)$$

where E_0 is the optical field amplitude of the input laser signal, $\omega = 2\pi f$ its angular frequency, $\omega_{MAST} = 2\pi f_{MAST}$ the angular frequency of the EOM modulating signal, and K a modulation-power-dependent proportionality constant that relates change in phase with the amplitude of the modulating signal. Expanding the phase of the exponential term in Eq. 1 yields

$$E_{opt}(t) = E_0 e^{j\omega t} \sum_{n=0}^{\infty} \frac{1}{n!} j^n K^n sin^n(\omega_{MAST} t). \qquad (2)$$

After expressing the sine as the sum of two complex exponentials, Eq. 2 can be expressed in terms of harmonics of ω_{MAST} as

$$E_{opt}(t) = E_0 \sum_{n=-\infty}^{\infty} F_n(K) e^{j(\omega + n\omega_{MAST})t}. \qquad (3)$$

where the prefactors $F_n(K)$ are proportionality constants. The master comb, featuring a comb line spacing of f_{MAST} and centered around f, is then split into two branches in order to select two of its modes separately. Mode N is selected in branch #1, and mode M is selected in branch #2. M and N represent the order n of the selected term, as given by Eq. 3, and they can be positive and negative. The mode selection is performed via optical injection locking in a slave laser (SL) in each branch [6]. This process just produces two coherent optical tones with frequencies $f_1 = f + Mf_{\mathrm{MAST}}$ and $f_2 = f + Nf_{\mathrm{MAST}}$ in branch #1 and #2, respectively, as exemplified in Fig. 2. To achieve two THz combs with a slight offset in their repetition rates, branch #2 is further split into two sub-branches, and the mode in each of the sub-branches is again modulated by an EOM in order to generate two slave combs centered at f_2. Since the EOMs are driven by two RF generators with frequencies f_{REP1} and f_{REP2}, respectively, the resulting offset between the repetition rates becomes $\Delta f = f_{\mathrm{REP1}} - f_{\mathrm{REP2}}$. Both slave combs are then frequency-shifted by f_{AOM1} and f_{AOM2}, respectively, using two acousto-optical modulators (AOMs), and subsequently amplified by two EDFAs.

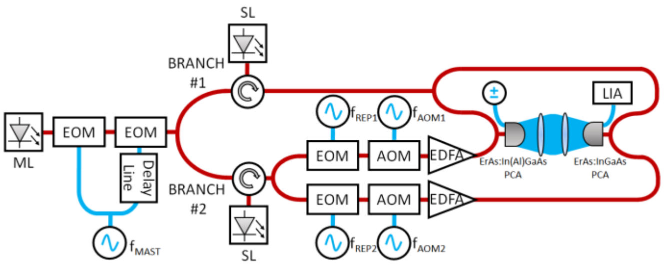

Fig. 1. Architecture of the electro-optic THz dual-comb.

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The THz comb is finally generated by photomixing the slave comb centered at $f_2 + f_{\mathrm{AOM1}}$ with the mode centered at f_1 from branch #1. The THz comb generated in the ErAs:In(Al)GaAs photoconductor is radiated to free space by its antenna. The emitted THz comb is received by the antenna of the receiving ErAs:InGaAs photoconductor, where the slave comb centered at $f_2 + f_{\mathrm{AOM2}}$ is photomixed with the mode centered at f_1 from branch #1. This produces a THz modulation of the photoconductor conductance, resulting in the mixing of the two THz combs, and ultimately in the down conversion of the emitted comb to a comb centered at the intermediate frequency (IF) determined by the difference between the frequency shifts imprinted by the two AOMs, $f_{\mathrm{IF}} = |f_{\mathrm{AOM1}} - f_{\mathrm{AOM2}}|$. A transimpedance amplifier (TIA) then amplifies the down-converted comb with a 10^6 V/A gain. Finally, a lock-in amplifier (LIA) with spectrum analysis capability acquires the down-converted comb, whose mode spacing is Δf.

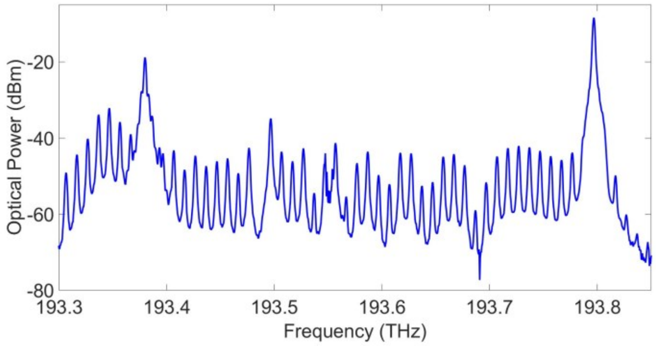

Fig. 2. Exemplary master comb generated by electro-optical modulation of the master laser output signal. The two modes, selected via optical injection locking, have a difference of 420 GHz for this exemplary case.

III. THZ PHOTOMIXERS

The photomixers used in this architecture are ErAs:In(Al)GaAs photoconductors, composed of a 10 µm x 10 µm area of ultra-fast photoconductive material covered by a finger-like electrode structure attached to a logarithmic-periodic antenna. The THz radiation emitted or received by the log-periodic antenna is further collected and focused by a 10-mm diameter silicon lens attached to photoconductor substrate. Examples of the electrode and antenna structure, the silicon lens, and the whole package used to interface them with the optical comb system are shown in Fig. 3 (a)-(d).

The photoconductive material used in the emitter is specifically engineered to withstand the high biasing (~9 V at CW excitation for a 2 µm gap) and relatively high currents ($\gtrsim$200 µA) required for medium power terahertz emission, while keeping the short carrier life-time (2.1±0.4 ps) required for a wide-bandwidth THz operation. This is achieved by means of a 90-period ErAs:In(Al)GaAs superlattice [7], where each period consists of 15 nm of i-InGaAs, 1.5 nm of p-doped InAlAs, 0.8 monolayers of delta-p-doped ErAs and 1.5 nm of p-doped InAlAs.

The photoconductive material used in the receiver is designed to exhibit a shorter carrier life-time than the one exhibited by the material in the emitter. It consists of a 100-period ErAs:InGaAs superlattice where each period consists of 10 nm of i-InGaAs and 0.8 monolayers of delta-p-doped ErAs. The resulting photoconductive material exhibits a carrier lifetime of 500 ± 50 fs. THz photoconductive receivers made from the same photoconductive material and using the same antenna and electrode structure feature NEPs as low as 1.8 fW/Hz at 188 GHz [8].

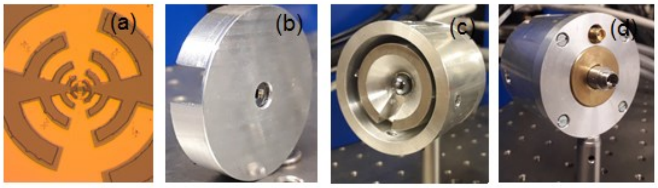

Fig. 3. ErAs:In(Al)GaAs photomixers used in the dual THz comb architecture. A microscope image of the log-periodic antenna is shown in (a), the silicon lens attached to the antenna together with its metallic holder is shown in (b), and the complete packaged photomixer is shown in (c) and (d).

IV. EXPERIMENTAL RESULTS

The THz dual-comb system was tested for several center frequencies within the 95.96 - 496.96 GHz range. For such tests, f_{MAST} was set to 16 GHz, f_{REP1} to 0.5 GHz and f_{REP2} to 0.5 GHz + 50 Hz. This resulted in a master comb mode spacing of 16 GHz, a THz comb spacing of 0.5 GHz, and down-converted comb mode spacing of 50 Hz. Meanwhile, f_{AOM1} and f_{AOM2} were set to 40 MHz and 40.275 MHz, respectively. This resulted in an IF of 275.5 kHz. The bias applied to the emitting photomixer was set to 5 V, while the optical power of the input combs was set to 30 ± 1 mW for both the emitter and the receiver. This resulted in a DC photocurrent of 80 µA for the emitter.

Fig. 4 shows the results for the highest center frequency tested, i.e. $f_{\mathrm{THz}} = f_1 - f_2 - f_{\mathrm{AOM1}} = 495.96$ GHz. To generate this center frequency, the difference between the mode numbers of the master comb selected in each of the branches was set to $M - N = 16$. The number of modes in the THz comb was then varied by changing the power of the RF signal driving the EOMs used for slave comb generation.

Increasing the RF power resulted in an increased number of modes given that the change in phase induced by the EOMs is directly proportional to the amplitude of modulating signal, as shown by Eqs. 1-3. Since the optical power was kept constant, the power of the individual modes decreases. The RF powers used for the three measurements shown in Fig. 4 were (a) 0 W (no modulation), (b) 1.2 W, and (c) 5 W. Each spectrum was acquired in 1.138 s using the spectrum analysis functionality of the LIA. In order to improve the noise performance, the spectra were averaged over 10 measurements. This results in a total acquisition time of 11.38 seconds. A maximum span of 15 modes with a peak THz dynamic range of 24 dB was achieved. This corresponds to an 8-GHz wide THz comb, covering from 491.96 GHz to 499.96 GHz.

The linewidth of the THz comb is on the Hz level as shown in [6], although one might anticipate a MHz linewidth due to the ordinary, unstabilized master laser used. Indeed, the master laser linewidth is about 1 MHz. However, the combs are generated by the RF modulation of the EOMs using high purity signal that is on Hz-level. Any frequency or phase change of the master laser is thus transferred synchronously to all comb lines, i.e. the lines “shake” synchronously. For THz generation, two of these comb lines are mixed, hence, any frequency offset caused by the finite linewidth of the master laser cancels out. What remains is the linewidth and stability of the RF generators driving the EOMs. The setup shown in this paper does not allow to measure the linewidth directly as all optical signals are mutually coherent. A direct proof of the linewidth of a sub-THz signal generated in the same way is shown in [6].

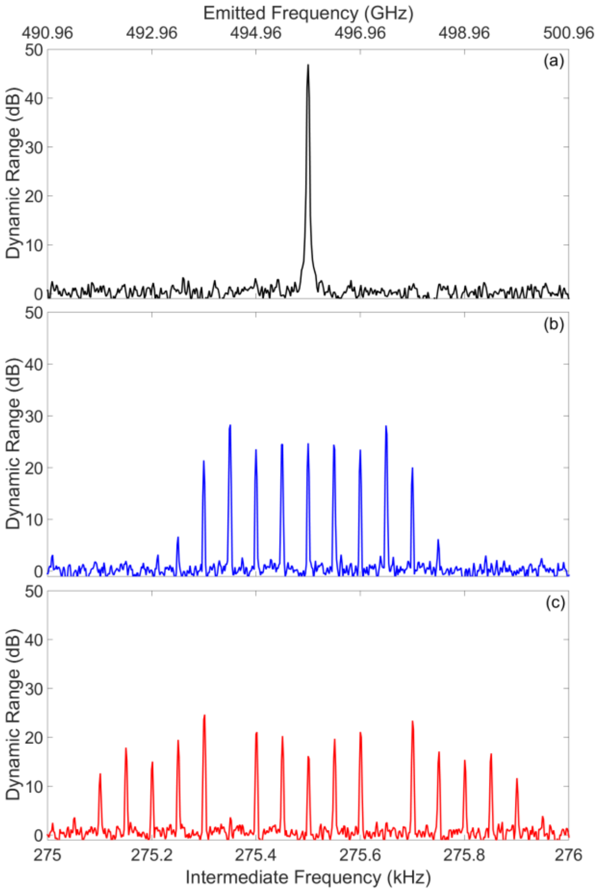

Fig. 4. Captured spectrum showing the direct mapping between the THz domain and the IF domain when f_{THz} was set to 496 GHz. The RF power applied at the slave-generating EOMs in each case was: 0 W (a), 1.2 W (b) and 5 W (c).

V. CONCLUSIONS AND OUTLOOK

A continuously tunable THz dual-comb with selectable comb spacing and Hz-level linewidth was presented. The maximum demonstrated tunabilty range of the comb center frequency was 495.96 GHz. The maximum dynamic range achieved for an individual THz mode was 47 dB, while the widest generated THz comb spanned 15 modes in 0.5 GHz steps, covering a total spectral width of 8 GHz. Both figures of merit were achieved with an acquisition time of 11.38 s.

The upper limit center frequency can be extended by incorporating non-linear fibers and gain switching in the master laser. In conjuction with the electro-optical modulation approach presented here, such techniques can produce optical frequency combs spanning 1 THz [9].

The dynamic range and/or acquisition time can be improved by using transmitting photomixers with a higher THz output powers, such as p-i-n diode based photomixers [10].

The span of the THz comb can be significantly increased by using higher RF frequencies with the appropiate amount of power to drive the slave combs. Hence, we anticipate that with the inclusion of two wideband amplifers within the sytem, the THz dual comb can easily reach a span of around 100 GHz with a tunable center frequency in the range of 50 GHz - 1 THz.

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