Enhancement of Terahertz Spectra by Model-Driven Spectral Shaping of a Mode-Locked Laser Diode in a Terahertz Time-Domain Spectroscopy System

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***Abstract*—In this work, we show first results of spectrally shaping the output of a mode-locked laser diode (MLLD) in a terahertz time-domain spectroscopy (THz-TDS) system with a programmable optical filter. The coefficients of the programmable optical filter are found with a genetic algorithm based on an analytical model that relates the detected terahertz spectrum to the optical spectrum of the MLLD. We define two different fitness functions for the genetic algorithm to deliberately impress desired properties on the detected terahertz spectrum. With the first fitness function, we achieve an increase in signal amplitude of up to 8 dB at the upper end of the terahertz spectrum. With the second fitness function, we flatten the terahertz spectrum between 150 and 950 GHz.**

I. INTRODUCTION

Terahertz time-domain spectroscopy (THz-TDS) systems employing monolithic mode-locked laser diodes (MLLDs) are attractive due to their compactness and significantly lower cost compared to femtosecond fiber laser-based systems [1], [2]. However, their bandwidth is still comparatively small and has been found to depend strongly on the shape of the MLLD spectrum [3]. Thus, one promising approach to improve the performance of THz-TDS systems employing MLLDs is the optimization of the optical spectrum. To facilitate this optimization, we have developed an analytical model that is able to predict the THz-TDS spectrum from the complex optical spectrum of the MLLD through the relationship [4]:

$$i_{\text{det}}(\tau) \propto \sum_{m=1}^{N-1} |H_{\text{THz}}(mF)| \cdot \sin[2\pi mF\tau + \angle H_{\text{THz}}(mF)] \cdot A_m \, , \tag{1}$$

where $H_{\text{THz}}(mF)$ is the transfer function of the terahertz channel including the emitter and detector, F is the repetition rate of the laser, τ is the delay of the delay line, and A_m is a factor that depends on the complex optical spectrum according to [2]:

$$A_m = \sum_{k=m}^{N-1} \sum_{l=m}^{N-1} E_k E_{k-m} E_l E_{l-m} \cdot \cos[(\varphi_k - \varphi_{k-m}) - (\varphi_l - \varphi_{l-m})] \, , \tag{2}$$

where N denotes the number of considered laser modes, and E_k and φ_k denote the amplitude and phase of mode k, respectively. However, since the relationship between E_k, φ_k, and A_m is not injective, the required MLLD spectrum cannot be directly calculated from the desired terahertz spectrum. We choose a genetic algorithm to find the optimized amplitudes and phases. In this work, we show first results by shaping the output of a quantum dot (QD) laser with a central wavelength of 1565 nm and a repetition rate of 50.17 GHz from Fraunhofer HHI [5] using a Finisar Waveshaper 1000A programmable optical filter.

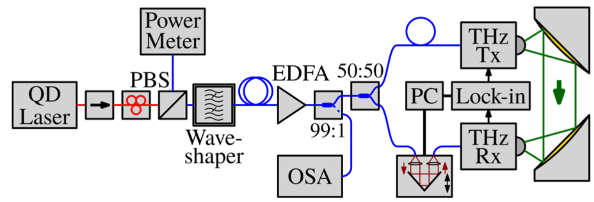

Fig. 1. Measurement setup for THz-TDS measurements with spectral shaping. The right half of the setup is a conventional terahertz time-domain spectrometer using an InGaAs emitter (THz Tx) and detector (THz Rx), both from Fraunhofer HHI, a fiber-coupled variable delay line, and a lock-in amplifier.

We use fiber-coupled InGaAs emitter and detector modules from Fraunhofer HHI that are designed for continuous-wave applications [6].

II. RESULTS

We use a conventional THz-TDS setup as depicted in Fig. 1. The input signal of the spectrometer is the spectrally shaped and amplified output of the QD laser. The intrinsic chirp of the laser is roughly compensated using a section of polarization-maintaining fiber. The chirp compensation is then fine-tuned by finding the dispersion coefficient of the Waveshaper that results in the minimum autocorrelation width, i.e. the minimum pulse duration. Based on the unshaped and chirp-free optical spectrum, we let a genetic algorithm, implemented in MATLAB, find the amplitudes E_k that result in the required terahertz spectrum according to the given equations. The amplitude coefficients of the Waveshaper are calculated from the desired amplitudes E_k and the measured optical spectrum of the MLLD. To enable a fair comparison between different results, the total optical power is kept constant with each optimization by tuning the injection current of the EDFA.

A. Maximum terahertz bandwidth

As a first attempt, we try to maximize the bandwidth of the terahertz spectrum. To that end, the genetic algorithm finds the amplitudes E_k that minimize the term

$$\frac{1}{\min\{A_m\}} \, , m \leq 25 \, , \tag{3}$$

i.e. that maximize the amplitude of the weakest spectral component in the frequency range from 50 GHz to 1.45 THz according to the analytical model without considering the transfer function of the terahertz channel. The genetic algorithm iteratively looks for the weakest spectral component in the terahertz signal and finds the amplitudes E_k that maximize the amplitude of that component. This way, one spectral component after the other is improved.

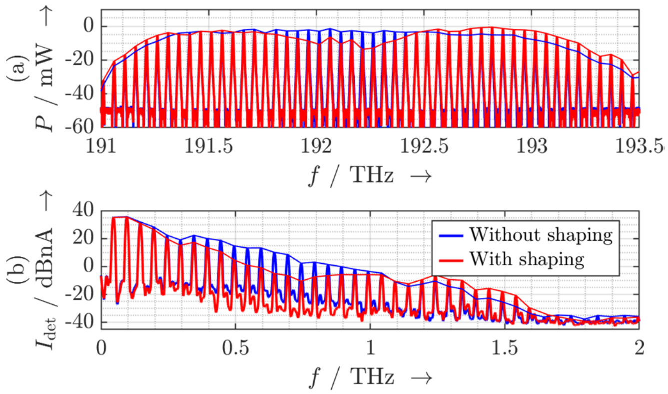

Fig. 2. Measured (a) optical and (b) terahertz spectra without (blue) and with (red) spectral shaping for maximum terahertz bandwidth.

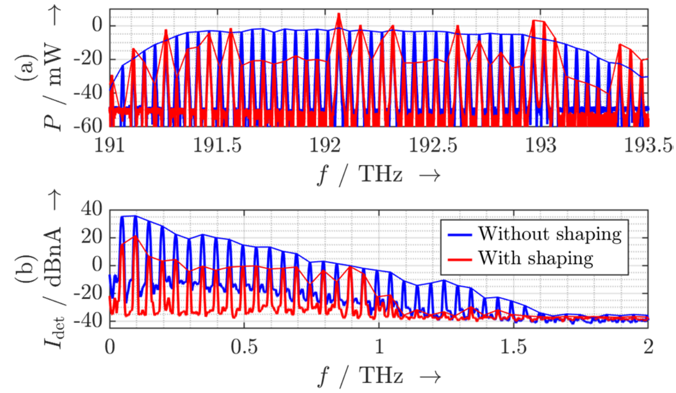

Fig. 3. Measured (a) optical and (b) terahertz spectra without (blue) and with (red) spectral shaping for a rectangular terahertz spectrum.

The unshaped and shaped optical spectra are depicted in Fig. 2(a). The measured terahertz spectra in Fig. 2(b) show an increase in signal amplitude of up to 8 dB for spectral components between 1.1 and 1.6 THz at the cost of spectral components between 0.2 and 1.1 THz.

B. Rectangular terahertz spectrum

The THz-TDS spectrum inherently drops off towards higher frequencies due to the decreasing number of summands contributing to A_m and due to the lowpass characteristic of the terahertz emitter and detector. We investigate the potential for equalizing the terahertz spectrum by spectrally shaping the optical spectrum of the MLLD. To realize a rectangular spectrum, we let the genetic algorithm find amplitudes E_k that minimize the term

$$\frac{{f_{\text{shape}}}^{1-a}}{{f_{\text{power}}}^{a}}, \tag{4}$$

where

$$f_{\text{shape}} = \frac{1}{24} \cdot \sum_{m=1}^{25} \left| \delta_m - \frac{1}{25} \cdot \sum_{n=1}^{25} \delta_n \right|^2 , \tag{5}$$

with

$$\delta_m = \frac{|H_{\text{THz}}(mF)| \cdot A_m}{\max\{|H_{\text{THz}}(mF)| \cdot A_m\}} - 1 , \tag{6}$$

and

$$f_{\text{power}} = \sum_{m=1}^{25} |H_{\text{THz}}(mF)|^2 \cdot {A_m}^2 \tag{7}$$

based on the analytical model of the THz-TDS system. The term f_{shape} describes the normalized deviation of the optimized terahertz spectrum from a flat spectrum, whereas the term f_{power} describes the total terahertz power. The parameter a balances the tradeoff between optimum shape and maximum power. Measurement results for the case $a = 0$ are depicted in Fig. 3. It can be seen from Fig. 3(b) that good flatness is achieved in the frequency range from 150 GHz to 950 GHz at the cost of terahertz power compared to the unshaped case. Higher terahertz power could be achieved at the cost of lower flatness by choosing $0 < a < 1$.

III. Conclusion

We have demonstrated the feasibility of model-driven spectral shaping in a THz-TDS system driven by a MLLD. The use of an analytical model that relates the detected terahertz spectrum to the optical spectrum allows us to let a genetic algorithm determine the optical spectrum that results in the desired terahertz spectrum. First experimental results show that by this approach the terahertz bandwidth can be increased or the terahertz spectrum can be flattened. Further work will aim at defining further optimization goals and improving the performance by feeding the measurement results back to the optimization algorithm. Furthermore, the concept of spectral shaping has the potential to be applied to other light sources, including superluminescence diodes, multi-mode lasers, and fiber lasers.

Acknowledgement

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