Broadband THz-TDS with 5.6 mW average power at 540 kHz with organic crystal BNA

S. Mansourzadeh¹, T. Vogel¹, A. Omar¹, M. Shalaby²,³, M. Cinchetti⁴, C. J. Saraceno¹

¹Photonics and Ultrafast Laser Science, Ruhr-University Bochum, Bochum, Germany
²Swiss Terahertz Research-Zurich, Technopark, Zurich, Switzerland
³Key Laboratory of Terahertz Optoelectronics, Beijing Advanced Innovation Center for Imaging Technology CNU, Beijing, China
⁴Department of Physics, TU Dortmund University, Dortmund, Germany

Abstract—We demonstrate a high dynamic range THz-TDS operating with high average power (5.6 mW) at 540 kHz repetition rate, with a broad bandwidth of 8 THz using the organic crystal BNA. The pump laser is an industrial Yb-laser system, temporally compressed to a pulse duration of sub-50 fs, and a high conversion efficiency of 0.1% is achieved.

I. INTRODUCTION

High power broadband Terahertz (THz) sources are widely used in THz time domain spectroscopy (THz-TDS) which is a well-known tool for many applications in THz science and technology. Optical rectification (OR) in nonlinear crystals is one of the most commonly used techniques to generate THz radiation. Due to the intrinsically lower dispersion of refractive index in organic nonlinear crystals, they are collinearly phase-matched in a much broader THz range in contrast to inorganic crystals [1]. In addition, their high nonlinear coefficient results in higher optical to THz conversion efficiency. However, due to limited crystal quality and poor thermal properties (compared to inorganic crystals) most results using those crystals were so far mostly limited to excitation with low repetition rate < 1 kHz pump lasers with high pulse energy and low average power. Only very recently, these crystals have started to be investigated in high average power regimes: HMQ-TMS and BNA (N-benzyl2-methyl-4-nitroaniline) were investigated at MHz repetition rate obtaining promising first results with milliwatt of THz power [2-3]. However, for spectroscopy applications, and in particular targeting nonlinear spectroscopies, multi-MHz repetition rates still yield rather moderate THz fields at very high average powers. Furthermore, tens of MHz could for some systems be too fast to allow the systems to be studied to relax from pulse to pulse. In this respect, repetition rates of hundreds of kHz offer an attractive middle ground for high-dynamic range, strong-field THz generation using well-established industrial-grade Yb-lasers.

In this work, we demonstrate a THz source based on OR in BNA at room temperature, driven by a commercial industrial laser system delivering 50 W of average power, operating at 540 kHz repetition rate. The pulses from the laser are temporally compressed from 240 fs down to 45 fs using a Herriot-type multi-pass cell (MPC). Our source reaches 5.6 mW of THz average power with broad bandwidth extending up to 8 THz at high dynamic range of 75 dB, with a conversion efficiency of 0.1%. To the best of our knowledge, this is the highest average power THz source achieved so far in BNA, improving the current state-of-the-art reported in [2] by factor of more than 5.

II. RESULTS

The experimental setup is shown in Figure 1. The driving laser is a commercial fiber-based laser (Carbide, Light Conversion) with a maximum average power of 50 W and a pulse duration of 240 fs. The current experiment is performed at a repetition rate of 540 kHz. In order to increase the efficiency of THz generation in BNA, an external compressor is required to shorten the temporal duration of the laser output. The Herriot-type MPC compressor consists of two highly-reflective-coated plan-concave mirrors with different radii of curvature (ROC) of 300 mm and 500 mm with a cavity length of 750 mm, achieving 26 passes, i.e., 13 roundtrips, through the nonlinear medium (fused silica). One of the two mirrors exhibits a GDD of -350 fs² per bounce which compensates for the material dispersion of the 9.5 mm fused silica plate. After the MPC, the pulse is compressed temporally to 45 fs by removing the chirp using negative dispersion mirrors. The output of the MPC is characterized using home-built second harmonic generation- frequency resolved optical gating (SHG-FROG) and an optical spectrum analyzer.

The THz radiation is generated by OR in a BNA crystal. The 1/e² diameter of the laser beam on the position of BNA is...
1.6 mm generated by a focusing lens with focal length of 300 mm placed before the crystal. To reduce thermal load on the BNA crystal an optical chopper with duty cycle of 50% is placed before the BNA crystal. The pump power is adjusted on the BNA using a combination of a thin film polarizer (TFP) and a waveplate ($\lambda/2$).

In order to fully characterize the THz radiation, three different methods are implemented: a calibrated pyroelectric powermeter (THz 20, SLT GmbH), a standard electro-optic sampling (EOS) setup or THz camera (RIGI Camera, Swiss Terahertz). To filter out the residual laser radiation and generated green beam after BNA, Polytetrafluoroethylene (PTFE) sheets with different thicknesses and black pieces of cloth are used. The data is acquired using a lock-in amplifier in combination with a data acquisition system which records the demodulated signal out of the lock-in amplifier and the digitized position of the shaker. A 0.5 mm GaP crystal is used to sample the generated THz trace using ~200 mW of the laser beam as the probe. Figure 3.a shows the THz power vs pump power on the crystal measured by THz powermeter. We can pump the crystal up to 4.7 W without any irreversible damage on the crystal. We reach a maximum THz average power of 5.6 mW with conversion efficiency of about 0.1%.

In order to estimate the THz peak electric field at the maximum THz average power of 5.6 mW, the THz powermeter is replaced by the THz camera in the EOS setup. Figure 4.a shows the THz trace in time domain averaged over 140 traces recorded in 70 sec. The corresponding power spectrum on the logarithmic scale is obtained by Fourier transform calculation from the measured THz trace and is shown in Figure 4.b. The spectrum has a wide bandwidth which spans up to 8 THz with a high dynamic range of about 75 dB, limited by the detection crystal response and the absorption bandwidth of Teflon filters.

In order to detect the full THz electric field, the THz powermeter is replaced with a 0.5 mm GaP detection crystal in the EOS setup. Figure 4.a indicates the THz trace in time domain averaged over 140 traces recorded in 70 sec. The corresponding power spectrum on the logarithmic scale is obtained by Fourier transform calculation from the measured THz trace and is shown in Figure 4.b. The spectrum has a wide bandwidth which spans up to 8 THz with a high dynamic range of about 75 dB, limited by the detection crystal response and the absorption bandwidth of Teflon filters.

III. CONCLUSION AND OUTLOOK

In conclusion, we show a high power, broadband, high dynamic range THz source pumped with 1030 nm laser at 540 kHz repetition rates with pulse duration of 45 fs. To get 45 fs of pulse duration, the output of the laser temporally compressed using Herriot type multi pass cell. Maximum measured THz power was 5.6 mW, which is the highest THz power recorded using BNA to the best of our knowledge. The calculated efficiency at the maximum THz power is 0.1%. This source represents a unique tool for a variety of time-resolved THz spectroscopy experiments, currently limited by dynamic range and bandwidth, potentially also with strong fields. Further THz power upscaling is possible into tens of mW by optimizing the cooling of the crystal i.e using cryostat and changing the duty cycle of the pump as it was studied in [3].

REFERENCES

[1] M. Jazbinsek, U. Puc, A. Abina, and A. Zidansek, “Organic Crystals for THz Photonics,” *Applied Sciences*, vol. 9, no. 5, Art. no. 5, Jan. 2019, doi: 10.3390/app9050882.
[2] T. O. Buchmann et al., “High-power few-cycle THz generation at MHz repetition rates in an organic crystal,” *APL Photonics*, vol. 5, no. 10, p. 106103, Oct. 2020, doi: 10.1063/5.0022762.
[3] S. Mansourzadeh, T. Vogel, M. Shalaby, F. Wulf, and C. J. Saraceno, “Milliwatt average power, MHz-repetition rate, broadband THz generation in organic crystal BNA with diamond substrate,” *Opt. Express*, vol. 29, no. 24, p. 38946, Nov. 2021, doi: 10.1364/OE.435344.