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D32.3
Report on the implementation of ultrashort intense THz sources with tailored properties

Lead Beneficiary: 10 (INFLPR)

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Deliverable Nature	
R = Report, P = Prototype, D = Demonstrator, O = Other	P
Dissemination Level	
PU = Public PP = Restricted to other programme participants (incl. the Commission Services) RE = Restricted to a group specified by the consortium (incl. the Commission Services) CO = Confidential, only for members of the consortium (incl. the Commission Services)	PU

A. Abstract / Executive Summary

Theoretical and experimental studies have been performed to develop high intensity THz sources with tailored properties. The techniques investigated include two-color filamentation, laser-plasma wakefield accelerator (LWFA), quantum cascade lasers. An enhancement of THz radiation is found, scaling like E^2 in the presence of a static transverse electric field and scaling like N^2 in the presence of N laser filaments organized in an array.

B. Deliverable Report

1 Introduction

Going beyond the mid-infrared spectral range we reach the terahertz domain (0.3 to 20 THz, 10 – 600 cm-1, 1 mm – 15 µm). THz is an exciting part of the spectrum since many interesting physical effects take place there. For instance, electrons in highly-excited atomic Rydberg states orbit at THz frequencies, small molecules rotate at THz frequencies and biologically-important collective modes of proteins vibrate at these frequencies. The use of ultrashort terahertz pulses is facilitating terahertz spectroscopy of a wide range of physical, chemical, and biological samples, and enables time-resolved measurements in which the terahertz pulse is used to probe dynamical responses to an optical excitation pulse. Recently, new approaches using intense ultrafast lasers have allowed for tabletop sources of ultrashort terahertz pulses approaching the µJ level in energy.

2 Objectives

Ultra-short and intense THz sources: targets the implementation and/or the improvement of tabletop ultra-short and intense THz sources. The development will be based on different approaches including large area photoconductive antennas and nonlinear crystals, phase matched generation using pulse front tilt, and generation schemes based on laser filamentation in gases.

3 Work performed / results / description

VULRC has analyzed both theoretically and experimentally the terahertz wave generation from air excited by tightly focused fundamental and second-harmonic pulses of a femtosecond Ti:sapphire laser for various pump pulse energies (0.4- 8 mJ) and durations of about 100 and 35 fs. Numerical calculations, based on the microscopic polarization model, revealed that the experimentally obtained dependencies of terahertz yield can be well explained taking into account phase shifts of bichromatic pump waves, acquired during free propagation in air, and nonlinear second harmonic crystal, as well as by considering the Gouy phases of focused laser beams [5]. In addition, at VULRC the dependence of spatial spectra (divergence) of generated conical THz emission on the focal length of focusing lens and pump pulse energy have been investigated experimentally and a total energy conversion efficiency of about 10^{-4} have been achieved. The bandwidth of registered few cycle THz pulses, measured by using a Michelson interferometer based on the Si wafer allowed us to estimate it as being of over 15 THz. The visible by naked eye plasma filament (up to a few cm in length) has been present during THz wave generation in all cases. Therefore in order to further investigate influence of preformed plasma on the efficiency of THz generation another laser beam was focused onto the main filament at a right angle, which increased plasma particle density in the overlap region of the filaments. It was found that THz yield strongly (by more than 30 percent) decreases immediately after the prepulse and then recovers with the time constant well corresponding to that of the plasma lifetime. Thus, this effect may be used for the fast modulation of THz power by the focused external laser beam.

STRATH have carried two studies into production of THz radiation using a a laser-plasma wakefield accelerator (LWFA). In the first one we have investigated the production of intense single-cycle pulses using coherent transition radiation, and measure THz bandwidths of more than 150 THz. This work has been submitted for publication. STRATH has also been working on a new mechanism for producing THz radiation from a laser-plasma interaction by exciting a localized and long-lasting transverse current using short laser pulses in weakly magnetized plasma. With moderate power driving laser pulses, the amplitude of the THz wave has a field strength of tens of MV/m, a frequency of a few THz. This work has been submitted for publication.

LENS demonstrated the phase-locking of a 2.5 THz QCL to a free-space THz comb generated by optical rectification of a femtosecond mode-locked Ti:sapphire laser. The combination of the absolute referencing provided by the THz comb with the mW-level power of the THz QCL allowed for a metrological-grade (a record-low 10 parts per trillion absolute frequency stability in tens of seconds) QCL-based THz spectroscopy with an unprecedented level of accuracy ($4\times10{-}9$ in the determination of a THz transition frequency). This simple direct absorption spectroscopy is only limited by the Doppler broadening of molecular spectra that does not allow to achieve the nominal precision of the THz spectrometer (about $5\times10{-}11$). Fortunately, the high output power provided by THz QCLs can enable sub-Doppler spectroscopic techniques based on non-linear saturation of molecular transitions in combination with cavity resonators. LENS demonstrated saturation effects in a rotational transition of CH3OH around 2.5 THz; moreover, it realized and characterized two different designs for resonant THz cavities, based on wire-grid polarizers as input/output couplers. The results were published in a series of papers [6-9].

CLPU in collaboration with the University of Salamanca has performed preliminary studies on chemical identification using a commercial Teraherz Time Domain interferometric system pumped with a Ti:Sa ultrashort laser, experiments on non-resonant (broadband) and resonant detection of terahertz radiation using strained-Si modulation doped field effect transistors, and experiments on generation and detection of THz radiation by using selfs-witching diodes pumped with a femtosecond laser.

FORTH has built a prototype THz-TDS system, based on ultrashort 2-color laser plasma filamentation that emit broadband intense THz pulses with tailored properties, Fig. 1. The source spectrum, intensity and polarization can be controlled by adjusting the filamentation parameters as is analytically described in our review in Chin. J. of Phys. **52**, 490 (2014). The system further to the tunability can be used for pump-probe experiments with pump or probe beams at wavelengths in the visible and the near infrared. Beyond the TDS system we have been investigating the physics of the 2-color filament THz source and have obtained valuable results on the spatio-temporal properties of the THz beam as well as on the way to increase the power of the source. Finally, we have been investigating novel materials, like metamaterials and eutectics for advanced dynamically controlled THz devices [11-17].

INFLPR implemented a high intensity THz pulses source based on multiple plasma filaments generated by a laser pulse of several 1 to 8 mJ energy and 50 fs pulse duration by two color filamentation method, Fig. 2 & 3. The THz pulses are in μJ range and the delay between pulses is tunable in 1-100 ps range. Multiple filaments were generated by using two methods: a-spectral clipping method; b- an assembly of thin film beam splitter polarizer attached to a high reflectivity mirror [10].

CNRS-LOA have shown previously that the THz emission from a single filament may be enhanced by the application of an external static electric field. We now consider the effect of a static electric field E on the coherent combination of THz emission from multiple filaments produced in air. An enhancement of THz radiation is found, scaling like E^2 in the presence of a static transverse electric field and scaling like N^2 in the presence of N laser filaments organized in an array, [1,2]. In a second scheme LOA study the THz radiation originating from two distinct filaments, either parallel to each other or forming an angle (Vee arrangement). For these two schemes the radiation pattern and the polarization properties of the total THz radiation were calculated and verified experimentally. Finally, using a Vee arrangement we proposed a method to spectrally enhance the effective THz radiation and to obtain circularly-polarized THz radiation, [3,4].

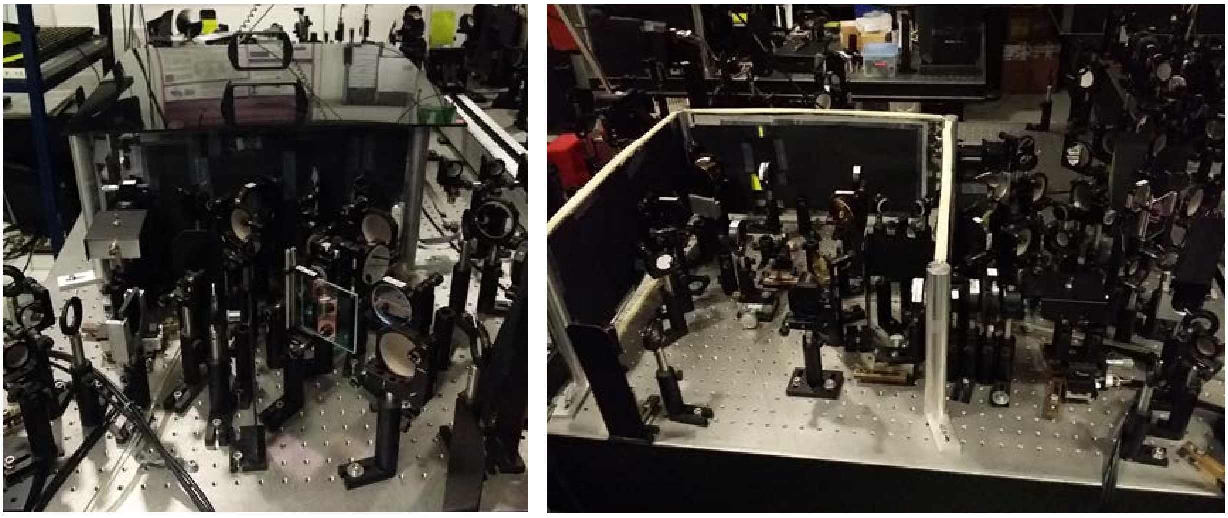

Fig. 1. The high power THz-TDS system developed at FORTH. Part of the system is placed in a purge gas chamber, used to avoid THz absorption from air humidity.

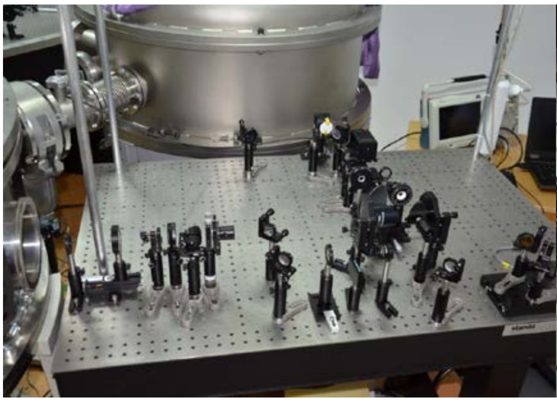

Fig. 2. The optical arrangement of high intensity multiple THz pulses generated by two color laser filamentation.(INFLPR)

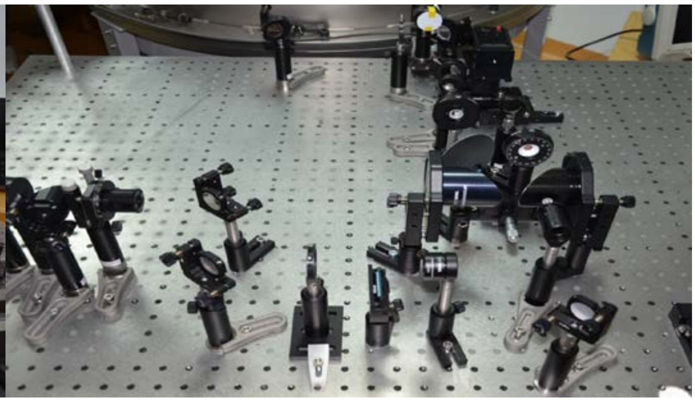

Fig. 3. Detail of the setup designed for multiple THz high intensity pulses with controllable delay between pulses: a) red & blue lines represents the optical pulses, b) yellow line represents THz pulses pulses path. (INFLPR)

4 Conclusions

This workpackage has been successfully completed; improved THz beam with tailored properties was demonstrated. Combination of THz emission from multiple filaments have been shown giving spectrally enhanced and circularly-polarized THz radiation. High intensity THz source with multiple THz pulses generated from the same optical pulse with a controllable delay was implemented.

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