Excitation of semiconductors and overdense plasmas with KrF laser pulses

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PhD thesis (summary)

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During the almost 60 years in the history of laser physics, a major milestone was the advancement of high power, short (< ps) pulse generating techniques. While their interaction with matter provides phenomena rich in physics just by their own merit, nowadays their application as a drivers for secondary light sources has become even more perspective. Such radiation sources as attosecond, coherent x-ray, or on the lower frequency range of the EM spectrum: terahertz radiation. The topic of my thesis were the study of the two above mentioned two phenomena. These fields are linked by the temporal and spatial coherence and the method of excitation itself. In the following I will summarize my main results in the form of thesis points.

In the first part of my thesis I present my experiments which I conducted within the framework of a canadian-hungarian joint experiment. I’ve demonstrated experimentally the applicability of Szatmári-type lasers in order to generate THz pulses from Photoconductive Antennas (PCA). I’ve compared the THz output and the efficiency of the antennas, made from differentsemiconductors.

The high breakdown voltage, and large band gap semiconductor based antennas were made from: ZnSe, GaN, 4H-SiC, 6H-SiC, and β − Ga2O3. With my experimental setup I’ve characterized the THz energy yields as a function of energy density, and bias voltage. Similar measurements were made using compressed laser pulses, although the picosecond timescale pedestals lowered the total THz yield. Large aperture antennas made from SiC were also tested, and peak THz energies were achieved in a high vacuum, biased at 64 kV/cm. Using this setup, a record pulse energy of 11 μJ was achieved (half-cycle operational mode) for photoconductive antennnas. I have also observed a strong linear relationship between the laser pulses energy contrast and the THz yield, for which I gave an approximate phenomenological explanation.

First thesis point:

I. Using experimental methods I have characterized photoconductive antennas developed from large band gap semiconductors. Using photoconductive antennas I’ve achieved the highest pulse energy (11 μJ) for a quasi-half cycle THz pulse. I’ve measured the relationship between the energy contrast of the pumping laser and the optical-THz conversion efficiency, for which I gave an approximate phenomenological explanation.

In order to spectrally characterize the THz radiation, I’ve designed and implemented a Michelson-interferometer. From the obtained waveform I’ve reconstructed the THz pulse length (2,2 ps), and the power spectrum as well. The spectral peak was located at 50 GHz, and the calculated ponderomotive potential, and THz el- ectric field strength was 60 eV, and 117 kv/cm respectively. The developed high power (6 MW) radiation source is capable for solid-state excitation experiments. In order to demonstrate this, I’ve built an experimental setup that was able to measure the nonlinear THz transmission enhancement of an InGaAs thin film sample. The enhancement maximum was around 1,7, which using a model developed by my canadian collegues can be interpreted as a THz field strength of 90 kV/cm. This is in good agreement with the results of the spectral analysis.

Second thesis point:

II. have designed and implemented a Michelson interferometer, which was capable to spectrally characterize the THz pulses from photoconductive antennas. Based on these findings I havedeveloped a THz radiation sour- ce and an experimental setup, in order to demonstrate the nonlinear transmission enhancement of an InGaAs thin film. From these results I’ve concluded that this radiation source with its extremely high ponderomotive potential is applicable in solid-state excitation experiments.

In order to properly interpret high intensity laser-plasma experiments, one has to take into account the role of surface perturbations caused by prepulses. This is true not only for KrF, but to all current and planned short pulse laser systems. In the second part of my thesis I have demonstrated the first application of the recently introduced laser contrast enhancement technique, the Nonlinear Fourier-filtering in a laser-plasma interaction experiment. This allowed me to examine such phenomena at record high (at this wavelength) 10^{12} intensity contrast. With these unique experimental conditions I have measured the reflectivity of boron and gold plasmas in an intensity range between 10^{15} W/cm^2 and 10^{18} W/cm^2. The intensity-, polarization-, and contrast dependence are in good agreement with earlier observations at lower intensities. However at high intensities the reflectivity drops due to the appearing nonlinear mechanisms such as resonance- and Brunel-absorption. By bypassing the filtering, the contrast dropped by more than six orders of magnitude, to around $5{,}5\cdot10^{12}$. Using these laser pulses I have demonstrated the significant effect of the prepulses caused by ASE (Amplified Spontaneous Emission). A home built diode based X-ray photodetector was used to measure the relative X-ray yields of different laser plasmas. Low laser contrasts resulted in significant increase of the total X-ray yield, which I interpreted as the effect of collisional dominated proceses occuring in the larger volume preplasma.

Third thesis point:

III. I have investigated the reflectivity of boron and gold targets using unprecedented intensity contrast KrF laser pulses. My experimental setup allowed to investigate the role of prepulses by controlling their intensity. The covered wide intensity range (10^{15} W/cm^2 – 10^{18} W/cm^2) showed a logarithmic decrese of reflectivtiy. Phenomenological explanation is given for the significant decrease of reflectivity at near peak intensities. I have compared the total x-ray yields of the laser plasmas generated in two different atomic number targets, and correlated the values to different laser parameters.

Useful information from the reflecting critical surface can be retrieved by examining its motion. This was achieved by spectral analysis of the main incident and reflected pulse. During my experiments I have found only significant blue shifts in the spectrum which indicates a plasma corona counter propagating with the laser pulse. At high intensities, above 10^{17} W/cm^2 this blue shift heavily depended on the contrast, and by using filtered pulses, the enhancement of blue shifts was about double, including all the two targets. The reported 0,6 nm blue shift was more than three times higher than earlier KrF experiments. The highest (indicated by the non-relativistic Doppler-formula) expansion speed of the plasma was around $6 \cdot 10^7$ cm/s. This was compared to another model, in which the incident and reflected pulse's bandwidth is compared. From this latter method, the maximum calculated acceleration of a boron plasma (excited with high contrast, high intensity, P-polarized pulses) was around $3{,}1 \cdot 10^{18}$ m/s^2, which is 50% higher than previous reports at this wavelength.

Fourth thesis point:

IV. Using spectroscopic methods I have investigated the motion of the critical reflecting surface. During the experiments I have observed a significant, intensity dependent blue shift of the excitation pulses, which indicates an expanding plasma front. Using high contrast pulses, the largest spectral shift of 0,6 nm can be attributed to the highest expansion velocity

of 6 $\cdot 10^7$cm/s. This value is more than twice compared to previously reported experiments with similar laser systems. From this, the inferred acceleration was $1{,}7\cdot 10^{18}$ m/s^2, which I compared to another method that includes the spectral bandwidth changes in the reflected laser pulse. This calculation yielded a maximum acceleration of $3{,}1\cdot 10^{18}$ m/s^2, which is in approximately good agreement with the more conventional method. In order to interpret the high expansion velocities near the peak intensities, I gave an approximate calculation that takes into account the local electron temperature and light pressure components.

Reffered journal articles supporting my thesis:

MTMT account number: 10052608

I.

X. Ropagnol, **Zs. Kovács**, B. Gilicze, M. Zhuldybina, F. Blanchard, Carlos,M. Garcia-Rosas, S. Szatmári, I. B. Foldes, T.Ozaki; "*Intense sub-terahertz radiation from wide-bandgap semiconductor based large-aperture photoconductive antennas pumped by UV lasers"*. New Journal of Physics 21(11), (2019)

II.

X. Ropagnol, **Zs. Kovács**, B. Gilicze, M. Zhuldybina, F. Blanchard, Carlos,M. Garcia-Rosas, S. Szatmári, I. B. Foldes, T.Ozaki; "*Intense sub-terahertz radiation from wide-bandgap semiconductor based large-aperture photoconductive antennas pumped by UV lasers"*. New Journal of Physics 21(11), (2019).

III.

Zs. Kovács, K. Bali, B. Gilicze, S. Szatmári and I. B. Földes; R*eflectivity and spectral shift from laser plasmas generated by high-contrast, high-intensity KrF laser pulses*. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences Volume 378, Issue 2184, (2020).

IV.

Zs. Kovács, B. Gilicze, S. Szatmári, I.B. Földes; "*Large Spectral Shift of Reflected Radiation From Laser Plasmas Generated by High Contrast KrF Laser Pulses"*. Frontiers in Physics, Volume 8, id. 321, (2020).