UNIVERSITY OF PÉCS

Physics Doctoral School

Nonlinear Optics and Spectroscopy Programme

Production of ultrashort light-pulses on the infrared and extreme ultraviolet spectral range

PhD Thesis

György Tóth

Supervisor:

Dr. János Hebling

Professor

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1. PRELIMINARIES AND OBJECTIVES

Plenty of books have been published about the incredibly wide use of high power ultrashort pulses [1-4]. Besides the inevitable role of femtosecond pulses in the examination of life sciences and chemical processes, nowadays the generation of isolated attosecond pulses receive outstanding attention [5]. Using these attosecond pulses, the motion of the electron in the atom has become observable [6]. On the other hand, few cycle intense light pulses at the near infrared spectral range can be used for the manipulation of ultrafast electron beams.

The topic of my Phd Thesis is the generation of ultrashort (consisting of a few cycle) light pulses on the infrared and extreme ultraviolet spectral range. The materials have very different optical properties on these two spectral ranges, therefore there is a need to elaborate new techniques in order to generate ultrashort pulses on these two spectral ranges.

In the first chapter of my thesis, I show the design of an optical parametric chirped pulse amplifier (OPCPA), which can generate few cycle extremely high energy pulses on the infrared spectral range.

My goal was to design an OPCPA, which can produce ultrashort pulses with extreme large energy from wide enough broadband pulses. Extreme large energy generation requires large aperture and high-quality nonlinear material having large nonlinear coefficient. For this purpose lithium niobate (LN) is semmed to be the most appropriate which is widely used at researches of the University of Pécs Institute of Physics and by other research groups [7], [8-12].

Choosing the pumping laser was a further aspect, so I decided upon a device, which had already produced pulse energy exceeding the joule-level. Therefore, my choice was the Yb:YAG laser working at 1.03 μm with which energy over 10 J was reached [13]. Broadband amplifying by 1.03 μm pumping, was previously possible only over the 2 μm wavelength range [14]. I showed that there is an opportunity for high broadband amplification on shorter wavelength range based on the angular dispersion technique [15].

The generation of ultrashort attosecond pulses based on coherent undulator radiation is presented in the second part of my dissertation. The time duration of ultrashort pulses generated on extreme ultraviolet spectral range is shorter than 1 fs.

The widest-spread way to generate attosecond pulses is the technique of high-order harmonic generation (HHG) in noble gas. Based on HHG technique it is possible to generate such ultrashort pulses with a few optical cycles [16-18]. In such cases the stability of the carrier-envelope phase (CEP) of the sequentially generated attosecond pulses is crutial [19]. Based on numerical calculations there is a way to influence CEP in the case of ultrashort attosecond pulses generated with HHG technique [16], but its control similarly as for the case of femtosecond pulses is impossible [20-22].

With the direction of Dr. János Hebling, Zoltán Tibai and me elaborated a technique based on electron manipulation and undulator-radiation, which enabled us to generate extremely stable, ultrashort attosecond pulses having preliminarily tailored CEP. The calculations of electronbunch manipulation in the project were done by Zoltán Tibai. My task was the simulation of manipulated electron bunch passing through short planar, respectively helical undulator and determination of electromagnetic radiation generated by electrons.

2. METHODS

According to numerical calculations I derived the necessary angular dispersion of the signal pulse in the LN which can produce perfect phase matching. Thereafter the derived function was approximated – with reasonable constraints – to the angular dispersion attributed to the setup containing a grating pair and spherical mirror. The least squares based fitting made possible the determination of the characteristic parameters of the setup. Specifying the evolution of sign, pump and idler pulses in LN crystal were realized with the help of codes based on a nonstationary OPCPA model [23] written by me. Split-step algorithm was used for the solution of coupled differential equation system constituting the basis of the model.

I created a model, which calculates the trajectory of the relativistic electrons in the undulator and determines the resultant electromagnetic field emitted by electrons. The characteristics of the emitted radiation were examined in wide range of the undulatorparameter and undulatorperiod.

3. NEW SCIENTIFIC ACHIEVEMENTS

I. In Lithium Niobate (LN) at pump wavelength of 1.03 μm, I proposed a setup, which can produce the necessary angular dispersion for the approximately perfect phase-matching at 1.4-2.05 μm spectral wavelength range, utilizing the maximal ($\left|d_{eff}\right| = 4.83\ \mathrm{pm/V}$) value of the nonlinear coefficient. The fundamental elements of this setup are the grating pair and the imaging system. The propagation direction of the signal and the normal of incidence of the first grating surface makes an angle of 31.3°. The two gratings are making an angle of 3.8° with each other. The grating constant of the first and second grating are 1.513 μm and 1.344 μm, respectively. The demagnification of the imaging optics is 1:3.5. The angle between the normal of the crystal surface and the propagation direction of the signal (corresponding to 1.55 μm) is 13.89°. [S1].

II. I improved a non-stationary OPCPA model. The model takes into account the second- and third order nonlinear interaction between signal, idler, and pump pulses, and the dispersion of the pulses. I showed that our technique can produce 40% wider spectral gain than KTA can produce based on noncollinear phase matching technique. I showed that a two-stage OPCPA system based on signal angular dispersion can produce total energy gain of 10^7, 222 mJ output energy, 16 % energy conversion efficiency, 17 fs (3 cycle) Fourier limited pulse duration, and 13 TW peak power. The pump energy was assumed to be 198 μJ and 1.38 J in the first and the second stage respectively, and the initial signal energy was 20 nJ with 8 fs Fourier-limited pulse duration [S1].

III. I created a model, which calculates the trajectory of the relativistic electrons in the undulátor and determines the radiation emitted by electrons. Based on this model, I showed that the temporal shape of the electric field of the attosecond pulses generated by nanobunch follows the spatial shape of the magnetic field of the radiator undulator [S2-S5]. The carrier-envelope phase of the attosecond pulse can be arbitrarily set by adjusting the phase in the spatial distribution of the magnetic field of the undulator [S2-S4]. The standard deviations of the carrier-envelope phases of the generated pulses are 31 mrad and 13 mrad at 20 nm and 60 nm, respectively.

IV. I demonstrated that a nanobunch with large transversal size reduces the emission solid angle as compared to the radiation of a single electron. Therefore, the larger transversal size of the nanobunch results in smaller total energy of the attosecond pulse. The transversal size of the nanobunch decreases at the radiator undulator by increasing the energy of the electrons ($\propto \gamma$). As a consequence, the solid angle of the radiation increases with γ causing the total radiated energy to increase faster than γ^2 [S2].

V. I demonstrated that the energy of the generated attosecond pulse is proportional to K^2 below $K \approx 0.5$, followed by a saturation at $K \approx 1.5$. The reason of the saturation is that a larger K results in the transformation of the energy in to higher harmonics and for shorter wavelength destructive interference occurs. According to my calculations, the energy of the attosecond pulses for $K = 1.5$ are 64 nJ and 466 nJ belonging to 20 and 60 nm central wavelength, respectively [S4].

VI. I showed that if the planar radiator undulator is replaced by a helical undulator, the generated attosecond pulses become circularly polarized [S3].

4. ARTICLES RELATED TO THE TOPIC OF THIS THESIS

[S1] **Gy. Tóth**, L. Pálfalvi, L. Tokodi, J. Hebling, and J. A. Fülöp, *„Scalable broadband OPCPA in Lithium Niobate with signal angular dispersion”*, Opt. Commun. **370**, 250-255 (2016)

[S2] Z. Tibai, **Gy. Tóth**, M. I. Mechler, J. A. Fülöp, G. Almási and J. Hebling, *„Proposal for Carrier-Envelope-Phase Stable Single-Cycle Attosecond Pulse Generation in the Extreme-Ultraviolet Range”*, Phys. Rev. Lett. **113**, 104801 (2014)

[S3] **Gy. Tóth**, Z. Tibai, Zs. Nagy-Csiha, Zs. Márton, G. Almási and J. Hebling, *„Circularly polarized carrier-envelope-phase stable attosecond pulse generation based* *on coherent undulator radiation”*, Opt. Lett. **40** (18), 4317-4320 (2015)

[S4] **Gy. Tóth**, Z. Tibai, Zs. Nagy-Csiha, Zs. Márton, G. Almási and J. Hebling, *„Investigation of novel shape-controlled linearly and circularly polarized attosecond pulse sources”*, Nucl. Instr. Meth. Phys. Res. B **369** 2-8 (2016)

[S5] Z. Tibai, **Gy. Tóth**, Zs. Nagy-Csiha, J. A. Fülöp, G. Almási, J. Hebling and J. Hebling, *„Carrier-envelope-phase stable linearly and circularly polarized attosecond pulse sources”*, Proc. of FEL2015, Daejeon, Korea, MOP071

5. OTHER ARTICLES

[S6] C. L. Korpa, **Gy. Tóth** and J. Hebling, *„Interplay of diffraction and nonlinear effects int he propagation of ultrashort pulses”,* J. Phys. B **49** (3), 035401 (2016)

[S7] L. Pálfalvi, J. A. Fülöp, **Gy. Tóth** and J. Hebling, *„Evanescent-wave proton postaccelerator driven by intense THz pulse”*, Phys. Rev. ST Accel. Beams **17** (3), 031301 (2014)

[S8] R. Hegenbarth, A. Steinmann, **G. Tóth**, J. Hebling and H. Giessen, *„Two-color femtosecond optical parametric oscillator with 1.7 W output pumped by a 7.4 W Yb:KGW laser”*, J. Opt. Soc. Am. B **28** (5) 1344-1352 (2011)

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