Attosecond Light Switches

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Abstract: Generalized Double Optical Gating is a robust sub-cycle switch for generating ultra-broadband single isolated attosecond pulses. It is a promising approach to reach microjoule-level XUV pulse energy for attosecond pump – attosecond probe experiments.
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1. Introduction

When a high-power femtosecond laser pulse interacts with noble gas atoms, a train of attosecond pulses can be generated, which corresponds to high-order harmonics in the spectral domain [1]. For pump-probe experiments, single isolated attosecond are desirable. Various switching methods have been invented to extract a single attosecond pulse from the train [2]. Many of them require carrier-envelope (CE) phase-stabilized few-cycle high-power driving lasers, which limit the driving laser energy to the millijoule level. Because of the small driving laser energy and the poor conversion efficiency, the energy of the isolated attosecond XUV pulses is very low, typically a few nanojoules. In some cases, the XUV wavelength range covered by the attosecond pulses is narrow. We demonstrated that the Generalized Double Optical Gating is a powerful sub-cycle optical switch for generating broadband, single isolated EUV, XUV, and soft x-ray attosecond pulses, which have been used to produce 67 as pulses and to conduct attosecond transient absorption experiments [3, 4]. Furthermore, it was implemented with multi-cycle, >200 mJ driving lasers to upscale the XUV pulse energy [5].

2. Generalized Double Optical Gating

In 2007, the Double Optical Gating was proposed [6], which was demonstrated experimentally in the following year [7, 8]. It is a combination of polarization gating and two-color gating. The former makes use of the strong dependence of high harmonic generation yield on the ellipticity of the driving laser field [9], which was first proposed in 1994 [10]. The generation of an XUV continuum with polarization gating was demonstrated in 2005 by superimposing two counter-rotating, circularly-polarized, few-cycle pulses from a Ti:Sapphire laser with a certain delay[11, 12]. The field is only linearly-polarized over half an optical cycle in the middle of the laser pulse, where a single attosecond pulse is produced. The leading and trailing edges of the pulse are still circularly-polarized, where XUV emission is switched off. For multi-cycle driving lasers, the cutoff photon energy of the attosecond pulses is determined by the ionization saturation intensity of the target atom. It is advantageous to start with elliptically-polarized pulses to reduce the depletion of the ground state population of the target atom by the leading edge. Such pulses can be obtained by passing a linearly-polarized pulse through a birefringent quartz wave plate, a set of thin Brewster windows, and a quarter-wave plate, as shown in Fig. 1.

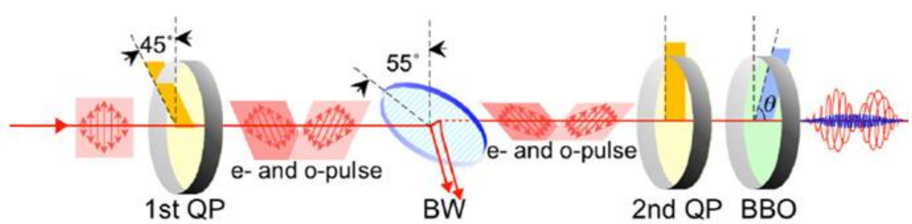

Fig. 1 Optics for Generalized Double Optical Gating [13]. The number of Brewster windows is used to vary the ellipticity of the two counter rotating pulses. The quarter-wave plate consists of a quartz plate and a second harmonic generation crystal.

The temporal spacing between adjacent attosecond pulses in high harmonic generation driven by a single-color laser is half of a laser cycle, whereas the on-and-off time of the polarization gating using optics in Fig. 1 can be expressed by the simple analytical equation [12, 13]

$$\delta t_G \approx \varepsilon \frac{\xi_{th}(q)}{ln2} \frac{\tau_p^2}{T_d},$$

where ε is the ellipticity of the two counter-rotating pulses, τ_p is the pulse duration, T_d is the time delay between the two pulses, and ξ_{th} is the ellipticity where the generation efficiency of the qth harmonic drops to 10% of the value for the linearly-polarized case. The gate width should be set to a value less than the interval of attosecond pulses in the train. For a given pulse duration, this can be accomplished by properly setting the time delay. However, the scheme fails if the pulse is too long. To maintain the driving field strength inside the polarization gate, the ionization probability of the atoms increases the time delay. The maximum time delay is determined by the full depletion of the ground state. The gate can also be narrowed by reducing ε. Its value cannot be too small, otherwise significant attosecond XUV emission occurs in the leading and trailing edges of the driving laser. The interval of attosecond pulses can be increased by a factor of two by adding a second harmonic field to the driving laser, which allows the usage of a wider polarization gate. Such a two-color gating can be realized by splitting the quarter-wave plate into two components as shown in Fig. 1. One of them is a second harmonic generation crystal such as BBO or LBO. When the ellipticity is set to 1, the attosecond switching scheme is called Double Optical Gating; for arbitrary ε values, it is called Generalized Double Optical Gating. Compared to other schemes, it tolerates much long driving lasers and larger CE phase jitter. At the Ti:Sapphire wavelength, pulses up to 28 fs in duration have been used successfully to generate isolated attosecond pulses using this method [13, 14].

2. Broadband and high-flux attosecond pulse generation with GDOG

Since the threshold ellipticity ξ_{th} is a weak function of harmonic order, Generalized Double Optical Gating works well simultaneously across the whole plateau and cutoff region of the high harmonic spectrum. We have demonstrated the generation of attosecond continua down to 12 eV and up to more than 500 eV. Such an EUV/x-ray supercontinuum is very attractive for attosecond transient absorption experiments since many energy levels of atoms and molecules can be covered at the same time [4].

Generalized Double Optical Gating can be implemented with multi-cycle lasers directly from Ti:Sapphire chirped pulse amplifiers [14], which paves the way for generating isolated attosecond pulses with microjoule-level energy. It is worth mentioning that only the driving laser energy inside the polarization gate has the potential being converted to photons of isolated attosecond pulses. Therefore, the shortest possible pulses should be used for driving the Generalized Double Optical Gating. We have developed a Ti:Sapphire laser system that is capable of producing sub-14 fs pulses with more than 300 mJ energy at 800 nm. Attosecond XUV continua with more than 100 nJ at 35 eV have been generated by driving the Generalized Double Optical Gating with this laser [5]. We are currently constructing a 200 TW driving laser to increase the XUV energy by another order of magnitude. This material is based upon work supported by Army Research office and the National Science Foundation under Grant Number 1068604.

4. References

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