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Ultraviolet Harmonic Beam Control via Spatial Phase Modulation of Driving Wavelength

Seungjai Won[1], Seungman Choi[1], Taewon Kim[1], Byunggi Kim[1], Seung-Woo Kim[1] and Young-Jin Kim[1,#]

1 Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Daejeon, Republic of Korea

Corresponding Author / Email: yj.kim@kaist.ac.kr, TEL: +82-042-350-3017

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Beam manipulation of short wavelength light sources, e.g., ultraviolet (UV) to extreme ultra-violet (EUV), is important in various industrial and research applications such as lithography, defect inspection, optical data storage, or encryption. However, beam control of those wavelength regimes is a challenging task due to the strong absorption characteristics of sub-UVs and lack of refractive-based optics. In this paper, we propose novel beam control method from UV to DUV wavelength based on nonlinear harmonic generation, which can emit a shorter wavelength than that of a driving beam. By controlling the spatial phase of the two driving beams using a spatial light modulator (SLM) and irradiating them non-collinearly to the nonlinear medium, we controlled UV second harmonics in real-time, while separating them from the driving beam. Based on the polarization-dependent phase controllability of SLM, harmonic waves can be switched to two different shapes by changing the polarization state of the driving beams. We also present the beam control of the third harmonics (deep-UV, 266 nm) using the MgO medium. This study presents a reliable platform for active spatial control of UV and DUV harmonics without special optical components for those wavelengths

1. Introduction

Short-wavelength light sources, e.g., ultraviolet (UV) or extreme ultra-violet (EUV), have been in great demand in industries such as lithography[1] and spectroscopy[2] due to their wavelength-scale resolution and high photon energy. For example, in semiconductor metrology industries, the use of short wavelength light allows to measure narrow linewidth[3] or inspect nanoscale defects[4] with high precision and high sensitivity[5]. In particular, UV-based optical encryption or data storage has attracted interest recently due to the large information capabilities and high security compared to visible (VIS, 400 nm ~ 700 nm wavelength) light[6,7]. For these applications, properties of short-wavelength light such as wavefront or spatial amplitude/phase distribution should be effectively modulated. However, beam control of those wavelength regimes has been difficult owing to the strong absorption characteristics and lack of refractive optical components.

Nonlinear harmonic generation, which can emit a shorter wavelength than that of a driving beam, can be considered an efficient tool for UV and EUV beam control. Focusing the phase-modulated driving beam into a nonlinear medium produces the spatial phase replica at the shorter harmonic wavelengths[8]. When controlling the driving beam, the use of the spatial light modulator (SLM) brings several advantages. First, it enables the dynamic modulation of harmonic waves. Second, the polarization-sensitive property of SLM[9] (diffracting only a specific linear polarization light due to birefringent liquid crystal) can give extended control capabilities depending on polarization state of the driving beam.

Here, we demonstrate real-time wavefront control of UV harmonic beams using a phase-modulative SLM. By controlling the spatial phase of the two sets of the driving beam and irradiating them non-collinearly to the nonlinear medium, we controlled UV harmonics (400 nm wavelength), while separating it from the driving beam. Based on this scheme, we demonstrated a novel harmonic pattern switching by selectively modulating only one of the two beams at the SLM. These two patterns are further controlled in real-time (7 frames/sec) based on the dynamic controllability of SLM. We also present the wavefront control of the third harmonic (deep-UV, 266 nm wavelength) using the MgO medium.

2. Experiments

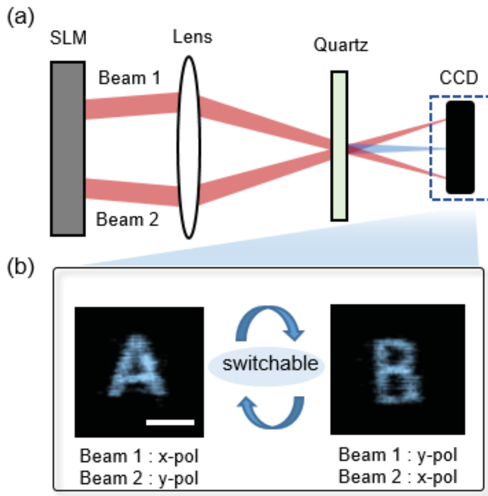
2.1 Second harmonic (UV) pattern switching

Fig. 1 shows the experimental configuration of UV harmonic beam pattern switching. The Ti-sapphire driving laser (800 nm wavelength, 40 fs pulse width, 1kHz repetition rate) is split into two beams of mutually orthogonal polarization by the Wollaston prism (WP). The polarization states of these two beams are set as horizontally and vertically, respectively, through a half-wave plate (HWP). When these two beams are incident in SLM, only one beam that has horizontal polarization is phase-modulated. The phase map was designed through an iterative Fourier transform algorithm to generate the desired pattern at the focal plane (CCD in Fig. 1(a)). The modulated or/and un-modulated two driving beams are set to same polarization by the Glanlaser polarizer (GP). By focusing and spatiotemporally overlapping those two beams into quartz medium (200 μm thick, Biotain) non-collinearly at 50 mm before the focal point, second harmonic wave is generated while separated from driving beam. The spatial phase information of this harmonic is rooted in that of the driving beam, therefore generating the desired pattern in the focal plane. Note that only the phase-modulated driving beam affects the shape of second harmonics. The propagation direction of harmonic waves in this non-collinear irradiation is defined by the momentum conservation of two driving beams as following equation[10].

$$k_q = q_1 k_1 + q_2 k_2$$

where k_1 and k_2 are the wavevector of driving beam 1 and beam 2, respectively. k_q is the wavevector of q-th harmonic beam, and q_1, q_2 represents the number of photons contributed by driving beams 1 and 2 to harmonic generation, respectively. The harmonic order q is equal to the total number of input photons from two beams (parity conservation; $q = q_1 + q_2$). In the case of second harmonics, both q_1 and q_2 are 1, so the propagation direction of the second harmonic has half of the angle between the two driving beams. Also, the pattern size of the second harmonic beam was half of the driving beam pattern. Fig. 1(b) shows pattern switching of UV second harmonics. By changing the polarization state of two driving beams using HWP before the SLM, the driving beam could be selectively modulated based on the polarization-sensitive properties of SLM. In this case, two different phase maps are input left and right in the SLM, therefore selectively modulated driving beams have different phase distributions. This induces pattern switching of generated UV second harmonic according to polarization condition of driving beams.

Based on the dynamic properties of SLM, the generated harmonic wave can be modulated in real-time. We input two sets of different phasemap in SLM sequentially (one is for generating "flower" pattern, the other one is for generating "pot" pattern) , and captured images each time according to two polarization conditions of input beams. Fig. 2(a) represents the sequential image of UV second harmonic when the driving beam have polarization condition 1 (beam 1 for x-pol, beam 2 for y-pol). In this case, the dynamically changing second harmonic wave is only affected by the phase information of beam 1. On the other hand, when the driving beam have polarization condition 2 (beam 1 for y-pol, beam 2 for x-pol) as Fig. 2(b), the UV harmonic is modulated in real-time only by the phase information of beam 2.



2.2. Third harmonic (DUV) beam modulation

We conducted spatial modulation of the 3rd harmonic DUVs using magnesium oxide (MgO) crystal (150 μm thick, <100>, Biotain). For generating a third harmonic wave, three photons of the driving beam are required. Therefore, there are two cases (2 photons from driving

Fig. 1 Configuration for harmonic beam modulation. (a) Experimental setup. SLM: Spatial light modulator. (b) Pattern switching of the harmonic beam.

beam 1, 1 photon from driving beam 2 or 1 photon from driving beam 1, 2 photons from driving beam 1) that satisfy the momentum conservation, and accordingly, the third harmonics propagate in two directions. A phase map is input into the SLM to generate the "h" pattern. The polarization states of two driving beams are set to polarization conditions 1 or 2. Fig. 3 (a-b) shows generated "h" pattern for driving IR and third harmonic, respectively from the left. It was clearly seen that the size of the third harmonic pattern has approximately three times smaller than that of the driving beam. This can be explained by Fraunhofer diffraction theory, the relationship of complex amplitude between far field (SLM) and focal plane (CCD).

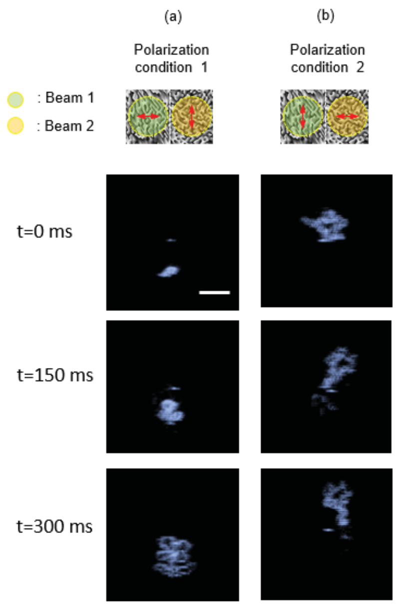


Fig. 2 Dynamic modulation of UV second harmonics according to the polarization state of two driving beams. (a) “Flower” pattern in polarization condition 1. (b) “Pot” pattern in polarization condition 2. The length of the scale bar is 400 μm.

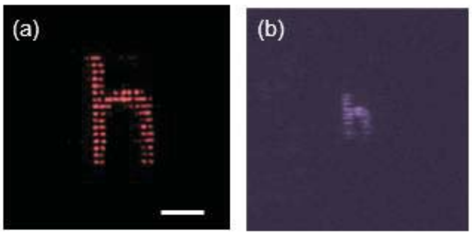


Fig. 3 Third harmonic beam modulation. (a) Generated letter “h” for driving beam. (b) Generated letter “h” for third harmonics. The length of scale bar is 200 μm.

$$g(x,y) = h_0 exp(-j\pi\frac{x^2+y^2}{\lambda d})\iint_{-\infty}^{\infty} f(x',y')exp(j2\pi\frac{xx'+yy'}{\lambda d})dx'dy'$$

where $f(x',y')$ and $g(x,y)$ represent the complex amplitude at the SLM plane and focal plane, respectively. The integral part is the Fourier transform of $f(x',y')$, denoted as $F(v_x,v_y)$. $v_x = x/\lambda d$ and $v_y = y/\lambda d$ is spatial frequency at the focal plane, which is affected by the wavelength of light. Therefore, the spatial frequency is higher in the shorter wavelength, inducing a decrease in pattern size.

3. Conclusions

We proposed a novel method for modulating UV harmonics based on SLM. By controlling the spatial phase distribution of two driving beams and irradiating them into nonlinear crystal non-collinearly, the phase-modulated UV harmonics were generated while separated from driving beam. Based on the polarization-sensitive phase controllability of SLM, we conducted pattern switching of UV harmonics according to the polarization states of two driving beams. This scheme could be implemented in real-time. We also presented the beam control of the third harmonics (deep UV wavelength) using the MgO medium. Our study presents a reliable platform for dynamic control of UV and DUV harmonics without special optical components for short-wavelengths, offering an efficient tool for UV pattering, polarization-sensitive optical encryption, or modulation of EUV beam.

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