High repetition rate extreme ultraviolet pulse generation with field enhancement

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We present experimentally that enhanced SPP(surface plasmon polariton) propagating toward end of tapered waveguide can produce high repetition rate EUV(extreme ultraviolet) pulses based on HHG(high harmonic generation) process. The generated EUV wavelength region is below 20 nm and repetition rate is 75 MHz same with original femtosecond laser. As a probe type, the suggested HHG method enables various prospective applications in scanning-mode near-field of EUV pulse, high resolution ultrafast microscopy and metrology.

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1. Introduction

Generation of EUV/X-ray has been researched extensively because their spectral regions correspond to a large number of energy transition levels related to atomic resonances and absorption. One way of generating EUV/X-ray is high harmonic generation (HHG)[1] resulting ultra-short pulse with superior coherence. The EUV ultra-short pulse enables us to monitor the electron motion in atom reaching its time scale up to level of attosecond. HHG is a nonlinear optical process in which an atom is ionized by high intensity over 10^{13} $\mathrm{Wcm^{-2}}$. Namely, it is very important to get such a high intensity for HHG from the perspective of ionization. Chirped pulse amplification (CPA) is generally used to amplify the laser pulse energy. However, CPA leads to not only a bit complex optical component system but also reduction of repetition rate. The repetition rate of pulse relate to the data acquisition time. In this study, we reported the generation of high repetition rate EUV pulse by plasmonic field enhancement. Especially, hollow metallic tapered waveguide was used here to boost up the electromagnetic field for maintaining original repetition rate of pulse instead of bow-tie nano-antenna array[2]. Design parameters of waveguide were analyzed by finite-difference time-domain calculation of electromagnetic field inside the waveguide. For the experimental validation, waveguide nanostructure was fabricated in commercialized micro cantilever probe using FIB(focused ion beam) milling process.

2. Tapered waveguide design and fabrication

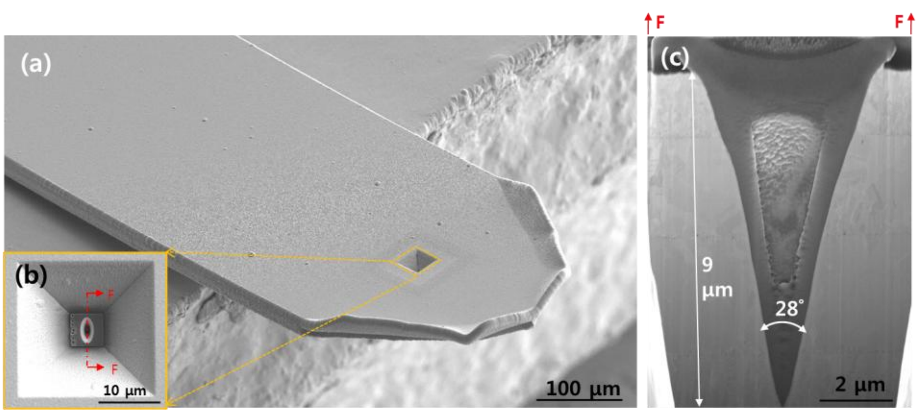

Fig. 1 Scanning electron microscope images of fabricated tapered waveguide. a, Top view of the cantilever based NSOM probe. b, Inlet of the tapered waveguide in the hollow pyramid. c, Cross section view of tapered waveguide.

When a femtosecond laser is focused into the hollow metallic tapered waveguide, the SPP is induced and propagating plasmonic field is enhanced near the end of waveguide due to accumulation of SPP energy[3]. Enhanced factor of SPP is greatly influenced by tapered waveguide shape. Therefore, we designed dimensional parameters of tapered waveguide based on FDTD(finite-difference time-domain) simulation results in order to get highest enhancement factor. The FDTD simulation condition is set as 800 nm center wavelength, 10 fs pulse duration and linearly polarized in the minor diameter axis. The intensity-enhancement factor exceeds 20 dB with a peak of ~350 over a volume of 350 nm × 350 nm × 450 nm in the x, y and z direction, respectively. Chosen values are tapered angle: 28°, exit aperture diameter: 200 nm along the major axis direction, length: 9 µm, and major and minor axis ratio is 0.5. We fabricated the tapered waveguide on the commercialized probe with FIB and fig. 1 shows the scanning electron microscope images of fabricated waveguide.

3. Experiment method and results

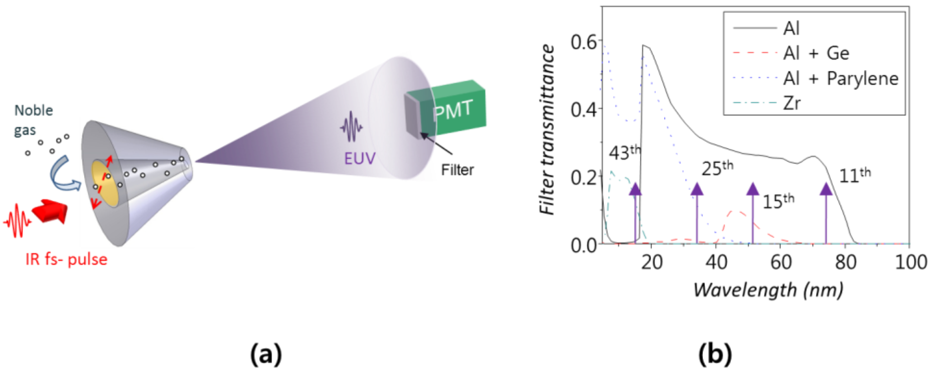

Fig. 2 a, Schematic diagram of experiment setup, PMT: photomultiplier tube. b, Graph of transmittance of filters in the EUV region; Al : 200 nm, Al: 200 nm + Ge: 200 nm, Al: 50 nm + Parylene: 200 nm, Zr: 500 nm.

Fig. 2 shows a schematic diagram of the experimental setup. Since generated HHG signals are easily absorbed in the air, all of the experiment parts are placed inside a vacuum chamber and we made a gas cell to inject the Xe gases into the tapered waveguide. The pulse energy of the incident laser was 1 nJ, 75 MHz repetition rate and the laser polarization direction is parallel to the minor axis of the tapered waveguide. Even though the pulse energy is not enough for HHG, the intensity enhancement factor exceeds 20 dB induce intensities stronger than the HHG triggering threshold of 10^{13} Wcm^{-2} from a moderate femtosecond laser oscillator. Due to the short dephasing time of SPP, generated EUV pulses also have a high 75 MHz repetition rate same with femtosecond laser. We experimentally detected the generated EUV photons by photomultiplier tube which was covered by 4 different EUV metal filters respectively. Those filters have different transmitted wavelength region, so we can easily analyze generated harmonic order approximately. We observed the EUV signal from all of the filters. Therefore, interaction with Xe gas, above 41st order was generated from a tapered waveguide.

4. Conclusions

We investigated HHG based on guided SPPs accumulated at the output side of a tapered hollow waveguide structure. We calculated the intensity enhancement factor by FDTD simulation and fabricated tapered waveguide on the commercialized probe with FIB as chosen design parameter values. From HHG experiment, it was experimentally verified that the incident pulse intensity is amplified by a factor of more than 20 dB at least, thereby can produce above 41st harmonics order successfully. Since the suggested plasmonic structure was fabricated onto a commercial probe, this method enables various applications such as scanning-mode near-field of EUV pulse, high resolution ultrafast microscopy and metrology.

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REFERENCES

1. Corkum, P. B., “Plasma Perspective on Strong Field Multiphoton Ionization,” Phys. Rev. Lett., Vol. 71, pp. 1994-1997, 1993.
2. Kim, S., Jin, J., Kim, Y.-J., Park, I.-Y., Kim, Y., and Kim, S.-W., “High-harmonic Generation by Resonant Plasmon Field Enhancement,” Nature, Vol. 453, pp. 757-760, 2008.
3. Stockman, M. I., “Nanofocusing of Optical Energy in Tapered Plasmonic Waveguides,” Phys. Rev. Lett. Vol. 93, 137404, 2004.