Plasmon-driven extreme-UV light

Joonhee Choi, Dong-Hyub Lee, Seunghwoi Han, In-Yong Park, Seungchul Kim, and Seung-Woo Kim

High-frequency radiation generated by nanofocusing packets of energy is opening the door for novel applications involving high-resolution near-field microscopy and lithography.

Extreme-UV (EUV) light of short optical wavelengths (below 120nm) is key to advances in many fields of science and technology. In microscopy and lithography, for example, this type of radiation improves the ultimate resolution achievable in imaging and patterning. Coherent EUV radiation is emitted by free electrons orbiting a synchrotron, but its use is largely limited to scientific research. For industrial applications, laser-produced plasma sources are being developed to generate high-energy photons from ionized (charged) atoms. However, EUV-generating plasmas require laser intensities higher than $10^{11}\text{Wcm}^{-2}$. These are not easily achieved with semiconductor or solid-state lasers. Moreover, plasma-based EUV sources are not coherent. In other words, they emit in all directions at many independent wavelengths.

We are investigating a ‘plasmonic’ method of generating EUV radiation that exploits the strong field enhancement typical of metallic nanostructures under illumination of femtosecond laser pulses. Surface plasmon polaritons (SPPs) are electromagnetic waves propagating along a metal-dielectric (insulating) interface. They result from coupling between incident photons and surface plasmons. In nanostructured tapered metallic waveguides with a hollow core, SPPs can be made to follow the geometric shape of the waveguide adiabatically (i.e., no loss by scattering or absorption). Inside the tapered hole, the forward-moving and backward-reflected SPPs are superimposed constructively to create an intense plasmonic standing wave near the tip where the local cross-sectional dimension becomes much smaller than the fundamental wavelength. Consequently, SPPs can be focused beyond the diffraction limit on a subwavelength spot with dramatically enhanced intensity. This intriguing phenomenon of SPP adiabatic nanofocusing can be used to generate EUV pulses directly from near-IR (NIR) pulses emitted from a moderate femtosecond oscillator without additional pulse power amplification.

Figure 1 shows a waveguide devised to demonstrate the plasmonic method of EUV light generation. The waveguide is a metallic nanostructure made of silver. Inside, it is hollow in the shape of a tapered cone whose elliptical cross section decreases from the inlet aperture of an ~2μm minor-axis diameter to the exit aperture of an ~30nm minor-axis diameter.2 We focus the incident NIR pulses on the inlet aperture at a 75MHz repetition rate with a moderate intensity of ~$10^{11}\text{Wcm}^{-2}$. As each NIR pulse propagates through the tapered hole toward the exit aperture, the electric field

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intensity inside the hole undergoes a substantial boost that is sustained by the SPPs driven by the incident NIR pulse. Gaseous atoms are supplied to the waveguide through control of the pressure difference between the inlet and exit aperture. The peak intensity-enhancement factor exceeds 20dB. Consequently, no additional pulse amplification is required to reach the threshold intensity that triggers ionization of gaseous atoms and emission of EUV radiation.

Two nonlinear frequency upconversion phenomena explain the atomic physics behind plasmon-driven EUV light: high-order harmonic generation (HHG) and atomic line emission (ALE). HHG occurs when the electric field of the driving laser is strong enough to ionize electrons by tunneling. The freed electrons are instantly recombined with parent ions as the electric field reverses in the next half-cycle. The resulting EUV radiation is coherent and appears in the spectral domain as a sum of high-order harmonics of the original frequency of the driving laser. HHG produces EUV radiation whose intensity increases with the second power of the gas density. In contrast, EUV radiation contributed by ALE is incoherent. As in the case of plasma-induced sources, it is emitted from bound electrons making energy-level transitions within the neutral and ionized atoms. ALE may coexist with HHG, but it has limited influence owing to intensities that are just proportional to the gaseous atom population.

Figure 2 shows a scanning electron microscopy image of a waveguide fabricated on a microcantilever using the focused ion beam process. Figure 3 presents EUV spectra measured from noble gas atoms (argon and neon). The spectra clearly show the high harmonics in the EUV radiation. Each harmonic peak has a wide bandwidth, indicating that the ultrafast plasmonic pulses formed in the hot-spot volume maintain the short duration of the incident NIR pulses. For argon, a broad spectral pedestal was found near H15–H17, which we presume is largely attributable to ALE. We observe no sign of ALE energies for wavelengths shorter than 40nm. The funnel waveguide not only improves EUV conversion efficiency but also confers immunity to thermal damage compared with previous attempts made using planar bow-tie- or rod-shaped nanostructures. Embedded on a cantilever tip, the waveguide structure is well suited to near-field applications of lithography and microscopy.

In conclusion, the plasmon-driven method of generating high-frequency radiation is emerging as a new tool to provide EUV sources for various applications, including near-field microscopy and lithography. In comparison to traditional methods, this approach can produce EUV light with high spatiotemporal coherence from a compact nanostructure. Further work is underway to improve conversion efficiency by further developing the nanostructure design to enhance output power for more practical uses.

Figure 3. Measured EUV spectra for noble gas atoms such as argon (Ar) and neon (Ne) interacting with the enhanced strong plasmonic field formed inside the funnel waveguide. H: Harmonic. a.u. Arbitrary units.
Author Information

Joonhee Choi, Dong-Hyub Lee, Seunghwoi Han, and Seung-Woo Kim  
Korea Advanced Institute of Science and Technology (KAIST)  
Daejeon, Republic of Korea

In-Yong Park  
Korea Research Institute of Standards and Science  
Daejeon, Republic of Korea

Seungchul Kim  
Max Planck Center for Attosecond Science  
Pohang, Republic of Korea

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