Design of efficient plasmonic nanodevice for coherent extreme-ultraviolet light generation

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In this report, more efficient plasmonic nanodevice for coherent EUV light generation is proposed, which is equipped with an additional cylindrical waveguide at the exit side of the tapered hollow waveguide with the aim of increasing the conversion efficiency of HHG by guiding the localized field through a long cylindrical waveguide to prolong the laser-gas interaction length. By analyzing waveguide dispersion equations, we quantitatively verified that generated power of EUV light will be proportional to the square of the laser-gas interaction length provided that the wave vector mismatch between propagating localized surface plasmon polariton (SPP) field and generated high harmonics is compensated by thin dielectric film deposition.

The proposed design of improved tapered waveguide structure will be a useful tool for future application areas such as EUV lithography, precision EUV metrology, high resolution EUV imaging, and so on.

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1. Introduction

Coherent EUV light source has a great potential in the field of high resolution (< 20 nm) lithography for semiconductor industry, non-destructive inspection for mechanical products, and chemical analysis for atomic/molecular spectroscopy due to its short wavelength (10 ~ 120 nm) and high energy (10 ~ 100 eV) characteristics. A few methods have been widely developed for generation of coherent EUV light source in a laboratory scale over the decades. Among them, HHG is a well-known method of achieving EUV/soft x-ray radiation by highly nonlinear frequency up-conversion process using an intense laser field [1].

Recently, it was demonstrated that a compact table-top sized EUV source can be realized by means of HHG based on either the surface plasmon resonance confined in the metal-dielectric surface of a metallic nanostructure [2] or adiabatic compression of propagating surface plasmon polaritons (SPPs) along a tapered metal-dielectric surface [3]; in the latter case, induced SPPs adiabatically get slow down as propagating toward the exit aperture of the tapered hollow waveguide structure and thus build up nano-localized field sufficient for triggering HHG process. We experimentally showed that coherent EUV light is generated even with a low energy (~ 1 nJ) laser pulse by the aid of plasmonic nanofocusing [4].

In this report, more efficient plasmonic nanodevice is proposed and analyzed, which is equipped with an additional cylindrical waveguide at the exit side of the tapered hollow waveguide with the aim of increasing the conversion efficiency of HHG by guiding the localized field through a long cylindrical waveguide to prolong the laser-gas interaction length.

2. Design methods & Numerical results

Originally, we performed HHG experiment with a 2-D nanostructure array composed of bow-tie-shaped triangular patches, but in the most recent we changed the shape of plasmonic structure into a 3-D tapered hollow waveguide structure to improve low harmonic conversion efficiency and thermal robustness. When a near-infrared femtosecond laser pulse is delivered into the tapered hollow waveguide structure, propagating SPPs are adiabatically compressed and thus build up nano-focused field near the exit aperture of the tapered waveguide. We experimentally showed that coherent EUV light is generated even with a low energy (~ 1 nJ) laser pulse by the aid of plasmonic nanofocusing. But harmonic conversion efficiency was still low (~ $10^{-7\sim-8}$) for broad EUV applications.

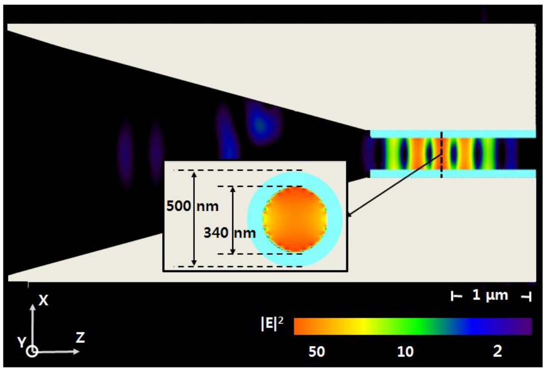
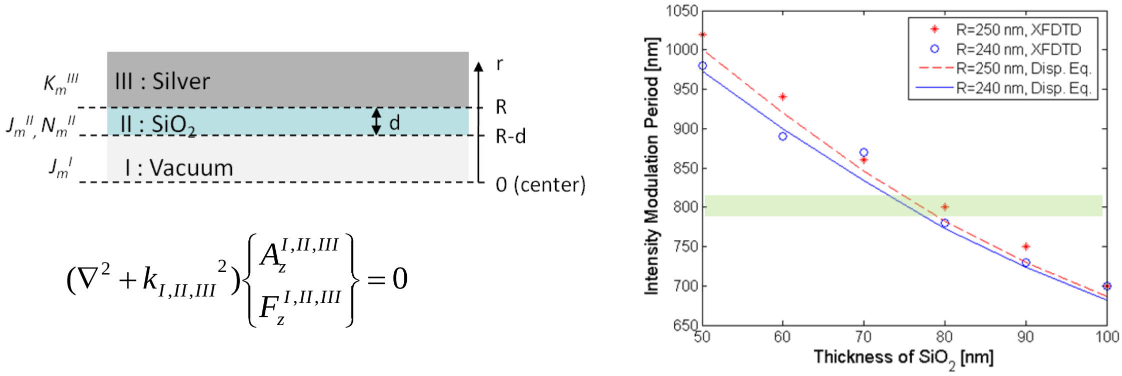


Fig. 1 Finite-difference time-domain (FDTD) simulation image of SPP field distribution within the attached cylindrical waveguide

Therefore, another modified version of plasmonic device is introduced, which is equipped with an additional cylindrical waveguide at the exit side of the tapered hollow waveguide. Fig. 1 shows that FDTD simulation image of near-field distribution associated with propagation of a SPP field in the proposed device. The amplified field can also propagate through a cylindrical waveguide after the tapered waveguide without critical energy loss. For efficient quasi-phase-matched HHG, a thin dielectric film with high refractive index is deposited along the inner wall of the cylindrical waveguide. By analyzing waveguide dispersion equations, Fig. 2 tells us that the thin dielectric film with the specific refractive index and the thickness can tune the spatial intensity modulation period precisely so that it can compensate the wave vector mismatch between propagating localized SPP field and generated high harmonics. This implies that harmonic conversion efficiency can largely increase by the prolonged coherence length leading to effective constructive interference of generated high harmonics. Assuming that perfect phase-matching is accomplished, harmonic conversion efficiency will be proportional to the square of laser-gas interaction length.



$$(\nabla^2 + k_{I,II,III}{}^2)\begin{Bmatrix} A_z^{I,II,III} \\ F_z^{I,II,III} \end{Bmatrix} = 0$$

Fig. 2 Geometrical modeling and numerical investigation on dependency of spatial intensity modulation period of propagating SPP field on the dielectric film thickness for efficient quasi-phase-matched HHG

3. Conclusions

The proposed design of improved tapered waveguide structure will lead to large increase in conversion efficiency, which in turn opens a wide way to access future application areas such as time-resolved pump-probe study, atomic spectroscopy, EUV metrology, and EUV imaging.

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