Angular dispersion boost of high order laser harmonics with dense plasma clusters

L.A. Litvinov1, A.A. Andreev1,2

1Saint Petersburg State University, Saint Petersburg, Russia

2Ioffe Physico-Technical Institute, Saint Petersburg, Russia

Abstract—Periodic surface gratings or photonic crystals are

excellent tools for diffracting light and to collect information

about the spectral intensity, if the target structure is known, or

about the diffracting object, if the light source is well defined.

However, this method is less effective in the case of extreme

ultraviolet (XUV) light due to the high absorption coefficient

of any material in this frequency range. Here we propose a

nanosphere array target in the plasma phase as an efficient

dispersive medium for the intense XUV light which is originated

from laser-plasma interactions where various high harmonic

generation processes take place. The scattering process is

studied with the help of numerical simulations and we show that

the angular distribution of different harmonics after scattering

can be perfectly described by a simple interference theory.

1. INTRODUCTION

Limited size targets interacting with high-intensity coherent radiation is well-studied phenomenon of linear excited surface plasmonic oscillations. Absorption and scattering of incident light in this case good described with Mie theory predicting exist of resonance corresponding to multipole oscillations of part of the target free electrons relative to positive charged ions. In resonance mode efficient exciting of surface plasmons can lead to significant boost internal and external field on fundamental cluster frequency (eigenfrequency). In turn, this can cause enhancement of field scattered on large angles relative to the direction of incident wave.

In micrometer wavelengths photon crystals and lattices can be used for direction or diffraction electromagnetic waves, while for x-ray radiation it is possible to use real crystals with regularly placed scattering centers (atoms) with distance of few nanometers. At the same time, large interval between these wavelength orders named XUV (extreme-ultraviolet) is hard to manipulate.

Within the present work we consider the possibility of directed scattering of short wavelength radiation in the XUV range by scattering on suitable spherical clusters. Similar case with cylindrical symmetry (arrays of nanocylinders as scatterers) was researched earlier. Of course, nanocylinders are more suitable regarding the control of size an distance parameters at the target manufacturing stage, but arrays of spherical clusters can make possible to manipulate with light direction in three-dimensional space and give a more optimal spatial configuration.

1. BASE MODEL
2. *Dielectric function*

Firstly we consider a single cluster with radius a irradiated by short femtosecond pulse with intensity about Ih = 1014 W/cm2. The Drude model yields the dielectric function of the plasma: (equation) - where ... .

1. *Mie Theory*

In the case of linear interaction Mie theory can be used for the description of elastic electromagnetic waves scattering by arbitrary sized particles and beyond that, it allows the description of the electric and magnetic ﬁeld distribution inside and outside the scatter. A main step is to solve the scalar Helmholtz Equation in suitable coordinate system and gain the vector solutions. For spherical cluster the solution of corresponding equation can be written in a spherical Bessel function of the l-th kind and n-th order the spherical harmonic including the associated Legendre polynomial.

Assume an incident plane wave propagating along z axis of cartesian coordinate system and polarized along x axis (equation).

Now we can expand the plane wave into series using generalized Fourier expantions. Assuming our media is isotropic we obtain following form of scattered field...

Coefficients in Eq have the following form...

1. *Resonance conditions*

To investigate the conditions under which resonant ﬁeld enhancement occur the determination of the desired coeﬃcients (\Autoref{an\_bessel, bn\_bessel}) is necessary in general. Since we are only interested in particle sizes which are smaller than the incident wavelength we use the limiting forms of the respective Bessel functions. In this asymptotic limit the coeﬃcients are of a much simpler form..

In this case amplitude of the scattered field is maximum for m2 = - (n+ 1) / n when ka << 1, that gain corresponding set of resonance densities in collision-less case

Eq. 6 can be used instead of Eq. 4, 5 for scatters with quite small radius, but for ka ~ 1 the approximation ceases to be reasonable already, particularly for large n. In this case the first-order approximation, that can be obtained including first term in polynomial expansion of Bessel functions, is better suited. Moreover, in first-order approximation dependency of coefficients on the scatter size occurs, which lead to corresponding dependency of resonance electron density.

Such approximations allow us to estimate the resonance cases for a material with pre-defined refractive index m as well as estimate refractive index corresponding to the required wavelength. As we consider XUV range radiation (20-120 nm), radiuses of spherical scatters should be about few nanometers, that causes ka ~ 1. Obviously, for such ka the resonance values of the electron density can be large in considering n = 1 as term with the largest contribution to the scattered field. Staying within high-temperature plasma we should use only ne < 1024 cm-3.

In first-order approximation with wavelength lambda10 = lambdaL / 10 = 83 nm, we have ne = 5.7 \* 1023 cm-3 for ka = 0.7 (a = 8.91 nm) to reach efficient scattering.

1. SIMULATIONS
2. *Scattering by an array*

Using resonance conditions obtained with analytical model, we consider diffraction by arrays of plasma clusters. Simple cubic lattice with N = 12 edge nodes and different grating constant d is considered spatial configuration of a volume grating. As the incident field we use gaussian beam with width w = 300 nm, that allow to assume the lattice as cluster layers by continuing cubic structure periodically along the entrance surface vector.

Diffraction orders can be obtained with Bragg's law.

According to Bragg's law we obtain theta = arcsin(1/4) for grating with d = 2\*lambda and theta = arcsin(1/6) for grating with d = 3\*lambda in 1-st diffraction order. Using these values we numerically compute the scattered field of 10-th laser harmonic with wavelength lambda10 = 83 nm, using CELES package, based on T-matrix calculations.

We can see directions corresponding to the angular boost of the incident beam, in particular, for d = 2\*lambda there are two fairly clear directions (Fig. 2), while for d = 3\*lambda there are three less clear ones with wider spread of the scattered field in general (Fig. 3).

CONCLUSION

The results show the correspondence of the Bragg-Wolfe diffraction theory for planar and spatial gratings, the ability to control high harmonics of laser radiation (XUV range) using an ionized cluster gas.