Efficient directed scattering of XUV radiation using high-density spherical clusters

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Hello, my name is Lev Litvinov and I'd like to present my work named "Efficient directed scattering of XUV radiation using high-density spherical clusters". My thesis advisor is Andreev Aleksandr Alekseevich.

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1 Introduction

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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.

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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.

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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.

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It is known that a short intense laser pulse can generate high-order harmonics by interacting with dense solid surfaces. But intensity of high-order harmonics generated in gases is at least 4 orders of magnitude less that is not enough to ionize the target and generate a plasma with fully imaginary refractive index that we need — in our case, spherical clusters are ionized cluster gas (Figure 1). To solve this problem we propose to use intense preceding pulse to pre-ionize the target and reach required plasma generation.

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Common interaction scheme is shown in Figure 2. Harmonics in the main pulse have different intensity depending on the angle, that leads to the angle dependence of output radiance shape. The scattering by a single cluster can be completely described in spherical symmetry and the interaction can be easily modeled with the help of particle in cell simulations. We propose to use linear approximation by Mie theory as assessment for further modeling. In general, we concentrate on a theoretical investigation, supported by simulations, and we point out the applicability for experimental realisation.
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2 Base model

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Let us consider a single cluster with radius a irradiated by short intense femtosecond pulse. Assume an incident plane wave propagating along z axis of cartesian coordinate system and polarized along x axis.

The Drude model yields the dielectric function of the plasma with corresponding parameters. The Mie theory can be used for the description of elastic electromagnetic wave scattering in case of linear interactions and let us obtain scattered and internal field. A main step is to solve the scalar Helmholtz Equation and gain the vector solutions. For spherical cluster the solution of corresponding equation can be written in the form of spherical Bessel and Hankel functions of n-th order with corresponding coefficients.

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Considering single cluster we can use zero-order approximation of Bessel functions if radius of the cluster is much less than wavelength. For values of normalized radius near 0.5 it's still applicable, but for $ka \sim 1$ the approximation ceases to be reasonable already, particularly for large orders of vactor harmonics.

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Instead, in this case, the first-order approximation is better suited. Here we can see how better this expansion — exact solutions are much closer to the first-order than zero-.

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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.

3 Single cluster

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Next we will consider several scattering computational experiments.

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Within the Mie theory, it is well-known that we can significantly enhance the field amplitude near the target. To check this, we will consider first and tenth laser harmonics in two cases of cluster radius: 0.5 and 0.7.

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Total near- and far-field was calculated to compare their amplitudes and scattering profiles. We can see, that the scattering of the laser harmonic (first harmonic) is very close to Rayleigh scattering — the incident plane wave profile almost does not change. The near-field amplitude value maximum is about fourteen.

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There is completely different situation for 10th harmonic — the incident plane wave profile is distorted as a result of scattering and becomes like a diverging spherical wave. The near-field amplitude is about 5 times higher than for first harmonic.

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Here is similar situation as for previously considered case with first harmonic - almost Rayleigh scattering without profile distortion and smaller maximum of the field amplitude.

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This case compared with similar situation for scattering by a single nanocylinder. We can see, that field distributions are similar include spherical outgoing far-field wave and localized near-field area in $0°$ scattering direction relative to the direction of the incident wave propagation.

4 Multiple clusters

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And we have results for simple cubic lattice scattering.

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It's described by folowing parameters: node radius a, number of nodes at the edge and unit cell length b. Field parameters are the same as for single cluster.

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Two cases was considered — with b equals to single wavelength and b equals to triple wavelength.

For the case of single wavelength we can see efficient scattering by facets of the spatial lattice. Most of the field is localized in the area of clusters.

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For triple wavelength due to the increased rarefaction between clusters allows us to get rid of strong reflection, which can be seen from the far-field.

It was shown that using the linear Mie theory, it's possible to quantify the resonance parameters of single cluster and predict potential scattering directions for multiple clusters.

Using the example of a cubic lattice location of high-density plasma spheres, was calculated options for diffraction control of the tenth laser harmonic for various of the lattice constants and revealed the features of scattering with respect to the angle incidence of radiation on the grating.

The results show the ability to control high harmonics of laser radiation in XUV range using an ionized cluster gas.

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Thanks for your attention.