Generation of phase-matched coherent point source in plasma media by propagated X-ray laser seeded beam

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Abstract. There is a significant interest in developing the coherent table-top X-ray lasers. Advent of plasma-based transient collisional excitation x-ray laser and particular, injection of coherent seeded beam, especially high-order harmonics, has tremendously improved the spatial coherence of such lasers, what allowed them to be the same widely used as synchrotron sources. Here we report experimental founding of unknown interference structure in a spatial profile of the output beam of the two-stage plasma X-ray laser. That allowed us experimental and theoretical discovering a new phenomenon consisted in a generation of phase-matched coherent point source in a laser plasma media by propagated X-ray laser seeded beam. This phenomenon could extend the applications of such x-ray lasers. For explanation of the observed phenomenon a new method of solving the standard system of Maxwell-Bloch equations has been developed. It was found that the interference pattern in the output laser beam was formed due to an emergence of phase-matched coherent virtual point source in the XRL amplifier and could be treated as the first observation of mirage phenomenon, analogous to the optical mirage, but in X-rays. The obtained results bring new comprehension into the physical nature of amplification of X-ray radiation in laser-induced plasma amplifiers and opening new opportunities for X-ray interferometry, holography and other applications, which requiring multiple rigidly phased sources of coherent radiation.

1. Introduction
Development of table-top X-ray lasers (XRL) \cite{1} and their application for investigations of XRL short pulse interaction with matter \cite{2} has an increasing interest during past years. Especially significant progress is achieved in development of multistage plasma-based transient collisional excitation X-ray lasers \cite{3}. Injection of coherent seeded beams \cite{4}, in particular high-order harmonics, in plasma-media...
of X-ray lasers allowed essentially improve the spatial coherence of such lasers and made them more attractive for different applications. Despite of such progress the radiation coherence of modern X-ray lasers is still not ideal and many scientific groups continue to work on improvement both the temporal and spatial coherence of x-ray laser radiation.

In this article we discuss an appearance of stable interference pattern in the output profile of XRL beam, discovered in [5], which allows proposing the generation of phase-matched coherent point source in amplifying plasma media by propagated X-ray laser seeded beam. The properties of such source are explained. An analogous of observed in x-ray spectral range phenomenon to optical mirage is shown.

II. Experimental set up and results

The experiments have been performed using the soft X-ray laser (SXRL) facility [3] at Kansai Photon Science Institute of Japan Atomic Energy Agency. The output laser pulses were generated with the Ni-like Ag plasma media using the oscillator-amplifier configuration shown schematically in Fig. 1. Thin silver foils for the oscillator and the amplifier were pumped, respectively, with the line-focused travelling wave laser pulses and with the proper timing for the effective amplification. A part of the SXRL beam from the oscillator was amplified in the plasma media of an amplifier. Emission spectrum corresponded to 4d – 4p transition of a nickel-like Ag ion at 13.9 nm wavelength. The SXRL pulse after the amplifier had a bandwidth narrower than $10^{-4}$ and pulse duration of ~ 7 ps. The SXRL system worked in 0.1 Hz repetition regime with the typical output energy of the order of 300 nJ.

![Figure 1. Scheme of the X-ray coherent mirage phenomenon observation caused by generation of imaginary source in amplifier plasma media, which is phase-matched to real source of XRL generator. In inset the focusing properties of plasma as the plasma lens are shown.](image-url)

In Fig.2 an image of output spatial-intensity distribution of SXRL measured by a high-resolution soft X-ray LiF detector at the distance of ~ 1300 mm is presented. Despite that the image was obtained in 30 consecutive shots a presence of concentric interference fringes in the image is clearly seen and indicates a high stability of the interference pattern formation. That is leading to conclusion that the phenomenon has a fundamental essence. Observation of such interference pattern requires presence of two coherent rigidly phased point sources. The first source is evident. It is formed by the oscillator. The appearance of second source is not obvious. To find location of second source additional experiments have been provided. In these experiments an output intensity distribution of the SXRL beam was measured in a single shot at the distance of 3,314 mm from the amplifier by means of X-ray back illuminated CCD. It was found that in the single shot images the concentric ring structure has high contrast (see Fig. 3) and could be recorded at the limited ranges of relative delays between pumping lasers (( ≤ 10 ps) and relative angles between oscillator and amplifier targets ( ≤ 0.6°).

Interference fringes were observed only in the two-stage laser operation mode, that is, when the generator and amplifier were turned on simultaneously (See Fig.4). The result of comparison of the
Figure 2. Far field intensity distribution of XRL beam measured by the LiF crystal X-ray detector after 30 XRL shots accumulation. Upper image and horizontal traces of intensity distribution (below) show presence of concentric interference fringes practically in the full view of the beam (the hexagonal mesh, placed in the XRL beam before detector, was used as a spatial coordinate’s reference).

Figure 3. Interference pattern in the far field intensity distribution of XRL beam measured by the X-ray CCD (upper). In zoomed parts of image the concentric interference fringes are clearly seen (center). Horizontal traces (below) show gradual decreasing of fringes period from left (closer to position of amplifier target) to right (far away from the target). The brighter area in the full image is the amplified XRL beam.
experimentally obtained interference pattern with the numerically calculated pattern is shown in Fig. 5 and allowed to determine that second point source is located at the distance $a = 203$ mm between sources in the center of the amplifier plasma.

![Image](image_url)

Figure 4. Output intensity distribution of the beam, if only generator is turned ON (upper) or only amplifier is turn ON (below). Interference fringes have not observed.

![Image](image_url)

Figure 5. (a) Experimental interference pattern; (b) Modeling of interference pattern for the case $a = 203$ mm; (c) comparison of experimental and modeled images in correspondent parts.

Provided scrupulous analyses [5] showed that standard Maxwell-Bloch equations, used for description of seeded beams amplification in plasma media, could not directly explain an appearance of two phased almost point sources and observed phenomenon. A new theoretical approach has been developed, which showed that observed effect is similar to formation of visible mirages in optically inhomogeneous atmosphere. The real and imaginary coherent sources could be created in plasmas of generator and amplifier. The difference to visible mirage consists in coherency of X-ray sources and their ability to interfere. The necessary and sufficient conditions for observation of X-ray mirage have been formulated [5]. It was demonstrated that plasma of laser amplifier could modify the x-ray laser wave front in the needed direction and behaves as X-ray optics (see also Fig.1). Moreover the measuring of the interference patterns themselves could be an effective method of diagnostics of X-ray laser plasma media, including the coherence degree of output radiation of such lasers.

Acknowledgments
This work is partly supported by JSPS Grant-in-Aid for Scientific Research Kiban (B) No.25289244 and by RFBR-JSPS collaboration program (RFBR Grant 14-02-92107

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