第12卷 第3期
1992年3月

光 学 学 报
ACTA OPTICA SINICA

Vol. 12, No. 3
March, 1992

Enhancement of brightness of laboratory soft X-ray lasers

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Abstract

A large separation "oscillator" source-travelling wave amplifier approach is suggested for attaining high power fully coherent X-ray source. Using a newly-designed aspherical lens combination, a long narrow focal line can be obtained, resulting in a more uniform and narrow laser-produced plasma column. It may be a great help to raise gain-length product.

Key words: soft X-ray laser, brightness.

The past few years have seen enormous progress in the field of generating and amplifying laser radiation in the soft X-ray regime. The development of laboratory soft X-ray lasers leads hope that these devices can serve as intense source of coherent X-rays. The goal of many of the researchers is to produce a bright, short-pulse, coherent source that would be ideal for the production of holograms of live, wet, biological specimen, affording an unique view into the structures of such live samples at resolution of about 30nm. Mathews et al.[1] predicate that one will need to produce at least 20μJ of spatially coherent radiation in a pulse-length of 50ps and focussed at the sample to a beam of 10μm diameter. High brightness of soft X-ray source is the most basical requirement for the holography applications. London et al.[2] conclude that wavelengths slightly longer than the 4.37nm carbon K-edge is an optimal wavelength choice for soft X-ray holography, Considerable attentions are also being aid to the study of the coherent characteristics of amplified spontaneous radiation obtained in laboratory systems[3~5].

Current laboratory X-ray lasers function as single-pass amplifiers without the benefit of feedback mirror and thus behave as amplifiers of incoherent spontaneous emission radiation. As a line-width of order 0.004nm was assumed (based on a theoretical predication of an ion temperature of 400 eV) for a 20.6nm wavelength selenium laser, its longitudinal coherence length, given by $\lambda^2/\Delta\lambda$, is about 100μm, which may be of great advantage in imaging biological objects more than 1μm in depth. But for a laser profile size of 100~200 μm and length of 2~4cm, it gives a lateral coherence length of 1~3μm, and the laser output end has an estimated 10^3~

Received 28 March 1991; revised 30 August 1991

10^4 transverse modes indicating poor spatiao coherence properties[4~6].

For applications that require coherence, such as holography, a laser that radiates in one or a few mode would be much more efficient. As the effective Fresnel number of the laser profile is decreased, the number of transverse modes decreases and so the degree of coherence increases. One way to make such a laser would be decrease its aperture, but this would also reduce the total output power. Simply increasing the length of laser gain medium to reach gain saturation is also no use for improving its coherence. Since these poor coherence properties are due to the fact that these lasers are highly multimode devices, adding gain saturation only worsens coherence properties. Rosen et al.[6] proposed a two-stage architecture for achieving powerful X-ray beams with high transverse coherence, namely, to produce a small-aperture (25 μm), spatially coherent beam in a first-stage laser, expand the beam with a spatial filter, and then amplify it in a large-aperture power amplifier. But there are many difficulties in both building-up a small aperture single-mode laser and mode-limiting with a spatial filter in practice. In the case of high power performance, the spatial filter which consists of multi-layer mirrors may be damaged by backward soft X-ray ASE radiation from the amplifier-stage, In addition, it should be noted that because there was no consideration on the time delay between the source and the amplifier, the coupling and interfering between them can not be avoided.

Based on our experiences in the development of high brightness, high energy Nd: glass laser facility, we suggest an approach of large separation "oscillator" source-travelling wave power amplifier to make bright X-ray source fully coherent. The main idea is to strengthen the amplification of axial fundamental mode and to limiting the excess spontaneous emission of off-axial higher modes, by means of properly enlarging the separation between the oscillator source and the power amplifier. Let us discuss how to butt the the oscillator source against the power amplifier. For the laboratory X-ray lasers of collisional excitation scheme at present[7,8], their typical parameters are: the output power $20\sim200\mu J/200\sim250ps=10^5\sim10^6W$, the wavelength $5\sim20$ nm, the output aperture $75\sim200\,\mu$m, the length of gain medium $2.5\sim4$ cm, the gain coefficient $2.5\sim4\,cm^{-1}$, the gain-length product $8\sim16$, the X-ray beam divergence $10\sim20$ mrad, which is well consistent with the geometric divergence of D/L. According to the well-known formula of lateral coherence length for an incoherent source propagating through free space, the transverse distance d over which a fully incoherent source of transverse size D (at a distance L away) looks like a fully coherent point source (at wavelength λ) is given by

$$d=L\lambda/D, \tag{1}$$

Using this formula we find, for $D=100\,\mu$m and $\lambda=10$ nm, a lateral coherence length $d=100\,\mu$m at $L=1$m, which is equal to the aperture size of power amplifier. Assuming the beam divergence of oscillator source is nearly about 10 mrad, the beam will illuminate a(10 mm)^2 footprint over a 1m distance. That means the(100 μm)^2 fully coherent area receiving only 10^{-4} of source signal. In other words, if there is an "oscillator" source which has a gain-length product of about 9, e. g. 3 cm$^{-1}\times$3 cm, amplifying factor being about 10^4, then we can get a single-mode signal strong enough at 1 m distance amplifier entrance; after propagating through the power amplifier which also has a performance of $GL=9$ and $D=100\,\mu$m, a diffraction-limited (order of 0.1 mrad divergence) fully coherent radiation output of energy about 20μJ could be expected. Otherwise, we may still prepare a second amplifier in the same way until to reach gain saturation. On the other hand, there must be a time delay $L/c=3.3$ ns, relative to the source for the amplifier pumping. This delay is quite long comparing to the driving laser pulse generally, then there will be a good isolation in time scale between the source and the amplifier. The amplifier can be controlled by intensive oscillator signal just from the beginning and works in a manner of travelling wave amplification. Furthermore, a high reflectivity multilayer mirror placed at a distance may be used in a small-size target chamber to fold the X-ray path and make two laser-produced plasma columns as close together as possible. This is a simple way to attain single transverse mode high brightness X-ray laser, especially in case of no refraction, i.e. the case of recombination pump scheme. Recently, X-ray laser experiments of two-slab targets set end to end oppositely were reported for the collisional excitation scheme[9,10], where the refraction effect is rather important. In these experiments, the separation of two targets was only about 1 mm, the time delay was about 90 ps. It is impossible to expect any obvious improvement in their coherence properties. If the separation and the time delay are enlarged enough, the improvement would be achieved. In this principle, a nuclear explosion driven X-ray laser can also get a diffraction-limited output beam.

Another issue in laboratory X-ray laser research is why the experiments with a long recombining-plasma column did not attain an estimated high gain-length product, in fact, the gain coefficient of only 0.5 cm^{-1} corresponding to a 6cm long plasma[11]. Here the refraction effect in condition of near 10^{19} cm^{-3} election density is unimportant. The effect of radiation trapping which leads to the reduction of population inversion density may be still serious after using a thinner target. But the uniformity of illumination along the line focus is a problem more worthy to be considered. X-ray laser studies require to produce a plasma column as gain medium. This is done by focusing the pump laser beam into a line focus. The usual technique is to use a aplanatic aspherical lens in conjunction with a positive or negative cylindrical lens. The line length may be varied by changing cylindrical lens power. A pair of weak crossed cylindrical lenses with a spherical lens makes it possibles to continuously vary the length of the focal line without refocusing. A shortcoming of this method is that the focal line axis maps directly from the near-field beam pattern. For a circular beam of uniform intensity the intensity along the line focus is highest in the center and drops to zero at the ends. The beam may be masked to provide a uniform rectangular beam which can give a uniform intensity distrobution, but at the expense of losing energy of the aperture. In any case, realistic beams are never perfectly uniform, so it certainly cause an inhomogeneous intensity distribution along the focal line.

Some new methods have been reported. An array of small cylindrical lenses before a spherical lens or an array of wedges in conjunction with a cylindrical lens were used to provide averaging over many segments of the laser beam resulting in a more uniform intensity distribution along the line focus[1,13]. But the problem has not been resolved thoroughly. The production of a large gain-length product needs a narrow plasma column of several centimeters long. However the existence of astigmatism and field curvature of a practical focusing geomtry results in the reduction of the pump laser irradiance, especially in the case of very long focal line. For a not very thick lens, no matter with spherical or aspherical surfaces, if it meets the aplanatic condition, its astigmatism and field curvature will be constant. Because the spread of light beam along the tangential direction only makes the focal line get somewhat longer, but in the sagittal direction it makes the focal line broaden, so that the product of sagittal field curvature and numerical aperture does determine the width of the focal line. That is to say, for an optical focusting system generally used in the X-ray laser experiment, when the length of the focal line is $2h$ and the numerical aperture is $2u$, the width w of the focal line at the distance h from the system center is given by

$$w=(1+1/n)h^2u/f, \tag{2}$$

where f is the focal length of the lens, n is the refractive index (or an averaging value of the refractive index in case of a lens combination). For example, if $f=400\,\mathrm{mm}$, $u=0.25$, $n=1.5$, $h=30\,\mathrm{mm}$, then $w=0.9\,\mathrm{mm}$. The broadening of the focal line causes serious decrease of the laser power density on the target. In order to correct sagittal field curvature, a new type of two-element lens combination which consists of one or two aspherical lenses can be designed, and the separation between these two lenses have to be large enough. Generally, the focal line width of less than $20\,\mu\mathrm{m}$ can be satisfied over a focal line length of 6 cm for a lens combination of 20 cm aperture and a focal length of 40 cm. Its circle of confusion on the axis $(h=0)$ is less than $5\,\mu m$ at the optimum image plane. For $h=22\,\mathrm{mm}$, the broadening of the focal line is about $10\,\mu\mathrm{m}$ due to the off-axis spherical abberation in the sagittal direction, while the tangential abberation has no contribution to it. The further experiment with this lens combination is arranged.

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增强实验室 X 激光的亮度

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(收稿日期：1991年3月28日；收到修改稿日期：1990年8月30日)

提　要

实验室X激光已经取得重大进展，但均属自发辐射放大，缺乏模式限制的措施，故激光功率分散在多横模中，提高激光亮度的措施之一是模式限制。由于X光多层膜一般为高吸收膜，用以形成谐振腔作模式限制看来是困难的。本文建议采用相距足够远的二段激光等离子体作同步延迟行波放大来进行横模限制。分析表明，达到衍射极限的单横模X激光是可能的，这对X光全息术以及高亮度X激光的实现是十分重要的。

本文还建议改变一般采用的产生线状等离子体的光学系统设计，使激光功率密度在长线上达到均匀；认为过去的光学系统不良是长焦线时，X激光增益-长度乘积低的一个可能原因。

关键词：软X射线激光，亮度