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**SELF-FILTERING UNSTABLE RESONATOR OPERATION
OF XeCl EXCIMER LASER**

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DELL'ENERGIA NUCLEARE E DELLE ENERGIE ALTERNATIVE

SELF-FILTERING UNSTABLE RESONATOR OPERATION OF XeCl EXCIMER LASER

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SUMMARY

A diffraction-limited laser beam with a pulse energy of 120 mJ and brightness up to a magnitude order of 10^{14} W cm^{-2} Sr^{-1} has been achieved in an x-ray preionized discharge XeCl laser by using a self-filtering unstable resonator. The near- and far-field laser properties have been examined.

RIASSUNTO

Un fascio ottico limitato per diffrazione con 120 mJ di energia per impulso e brillanza dell'ordine di 10^{14} W cm^{-2} Sr^{-1} è stato ottenuto in un laser a XeCl a scarica autosostenuta e preionizzato a raggi X utilizzando un risonatore instabile autofiltrante.

Oltre alle principali caratteristiche del fascio laser come la divergenza e l'evoluzione temporale del modo, è stata esaminata sperimentalmente l'influenza del filtro spaziale interno al risonatore ottico.

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INTRODUCTION

The operation of a high quality output beam from a Nd-YAG laser and a TEA CO_2 laser with a novel cavity design called "self-filtering unstable resonator" (SFUR) has been reported recently [1-3]. The idea of the SFUR is to place a spatial filter with a pinhole of radius $a = (0.61 \cdot \lambda \cdot f_2)^{\frac{1}{2}}$ (the SFUR condition) at the focus which is shared by the two cavity mirrors of focal lengths f_1 and f_2 in a confocal negative-branch unstable resonator [1] (Fig. 1a). Under these conditions, for a plane wave incident on the spatial filter and reflected back again by the cavity mirror M_2, only the Airy disk will pass the spatial filter, and, after reflection on the mirror M_1, it is magnified, collimated and presented Fourier-transformed at the spatial filter plane ready to begin another round trip.

Starting from the Fresnel principle and using the condition for magnification $M \to 1$ ($M = |f_1/f_2|$), some analytical results for the lowest order transverse mode of the SFUR have been deduced [4], and the main results are

i) the spatial profile of the mode intensity near the laser beam output coupler is

$$|E|^2/|E_o|^2 = \exp\,[-2.108\ r^2/(M \cdot a)^2 + O\ (1/M^4)]; \qquad (1)$$

ii) the fractional power loss of the laser beam per round trip is

$$1-|\gamma|^2 = 1 - (1.968/M^2) \cdot [1-0.6048/M^2 + O\ (1/M^4)]. \qquad (2)$$

Here, $O(1/M^4)$ is a small quantity of the order of $1/M^4$. Based on these formulas and the SFUR condition, a set of SFUR parameters has been chosen and successfully applied to a XeCl discharge laser.

EXPERIMENTAL SET UP

The schematic configuration of the SFUR is shown in Fig. 1a. The device used in our experiments is an x-ray preionized XeCl discharge system which is basically the same as that described in [5]. The discharge chamber is sealed by two Brewster angle fused silica windows and has an active length of 80 cm. Very lean mixtures (Ne:Xe:HCl = 2037:6.7:1)

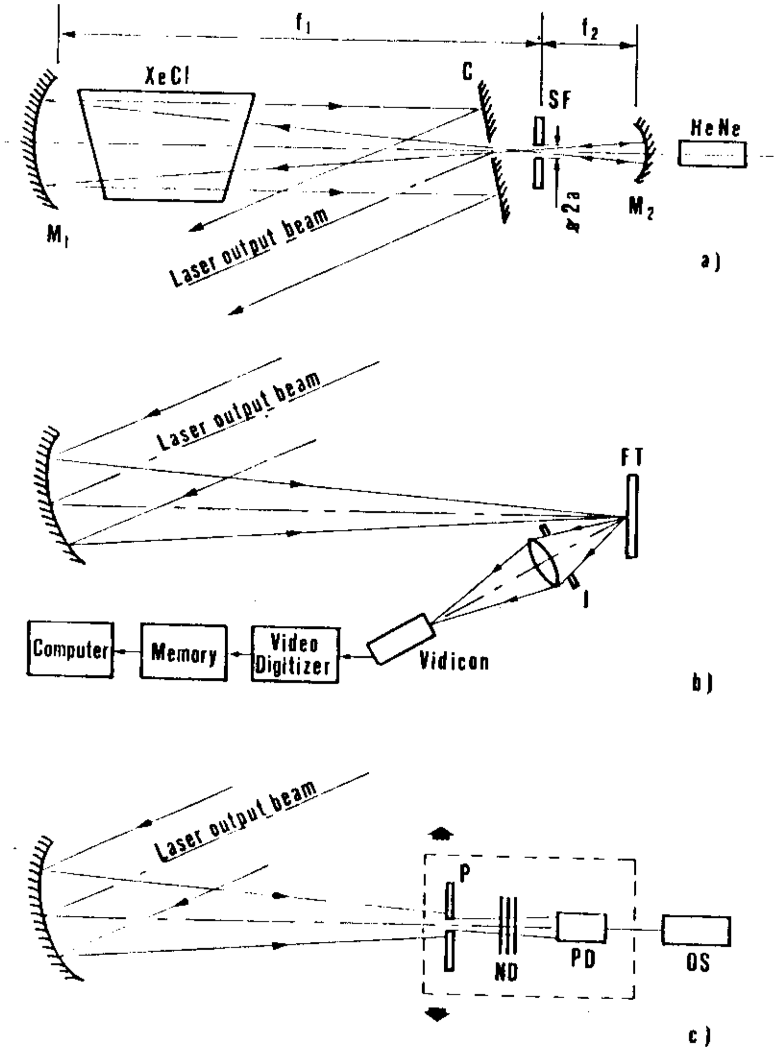

Fig. 1 - Schematic diagram of the experimental set up. a) SFUR configuration; b) Far field divergence measurement; c) Laser mode evolution measurement. M_1 and M_2 are totally reflecting concave mirrors with longer and shorter focal length f_1 = 5 m and f_2 = 0.5 m, respectively; C is the output coupler; SF is the spatial filter; FT is the fluorescence target; I is the iris; ND are neutral density filters; P is the pinhole with diameter ϕ = 0.4 mm; PD is the photodiode; OS is the oscilloscope.

were used for all our experiments. The pumping energy density of 0.27 J/cm^3 (the energy stored in capacitors/the discharge volume) was kept unchanged. The SFUR cavity with a magnification M = 10 used in these experiments consisted of two totally reflecting concave mirrors, M_1 and M_2, with a 10 m and a 1 m radius of curvature respectively.

A spatial filter SF, which was apertured with a circular hole of diameter 0.6 mm according to the SFUR condition, was placed at the common focus of the two mirrors, M_1 and M_2, separated by 5.5 m. A flat aluminized mirror with a hole was set near the spatial filter as a laser beam output coupler, slightly out of the perpendicular to the optical axis of the cavity.

The laser pulse energy was measured with a Gen Tec energy meter (type ED 1000). The time evolution of the laser intensity was measured by a ITT photodiode (type FW114A) and a storage oscilloscope (Tektronix 7834) in conjunction with some neutral density filters in order to keep the light intensity within the linear response of the photodiode.

The SFUR alignment was achieved with the following steps. First, the mirror M_1 was aligned by using a collimated He-Ne laser beam. The spatial filter and the coupler were then inserted and their holes were centered. Finally, the mirror M_2 was put in and aligned. The discharge system was run, and the mirror orientation and the pinhole position were gradually adjusted in order to obtain the maximum laser pulse energy. The alignment can be completed within half an hour. Due to the short wavelength and the long cavity length in this system, the alignment should be carried out very carefully. A 70% drop in output energy is produced by a mirror tilt or a spatial filter translation misalignment along a direction perpendicular to the optical axis within 1 minute of arc or 1·a, respectively. However, the laser system exhibited a good alignment stability. Although the SFUR system was propped up directly on the ground without using a special optical bench, it could work well for a few days without requiring further alignment or showing apparent degradation of either the laser energy or the beam quality. This may be due to the smaller misalignment and aberration sensitivity of the negative branch configuration with respect to the positive branch [6,7] for the same magnification.

NEAR-FIELD MEASUREMENT

The near-field laser spatial profile of the SFUR mode was examined in two ways. First, we employed a partly reflecting flat mirror as an output coupler instead of the coupler with a hole which we usually used. Because of the reflection loss of the flat mirror inside the cavity, the laser oscillation was just above the threshold and the laser output energy was only a few mJ. The laser intensity spatial profile near the coupler was obtained by measuring the laser power transmitted by the pinhole (0.4 mm-diameter) scanned along a direction perpendicular to the optical axis of the outcoupled laser beam. Figure 2 shows the results which are in agreement with the Gaussian shape (solid line) calculated from (1). Second, using aluminized flat mirrors with a hole as a coupler, we measured the outcoupled laser energy as a function of the diameter of the coupler hole. The results are shown in Fig. 3, where the solid line is calculated from a Gaussian profile according to (1). A laser extraction energy density of over 4 mJ/cm^3 was achieved considering that the mode diameter is 2 Ma $\doteq$ 6 mm ($1/e^2$ intensity points) and the mode volume is about 24 cm^3.

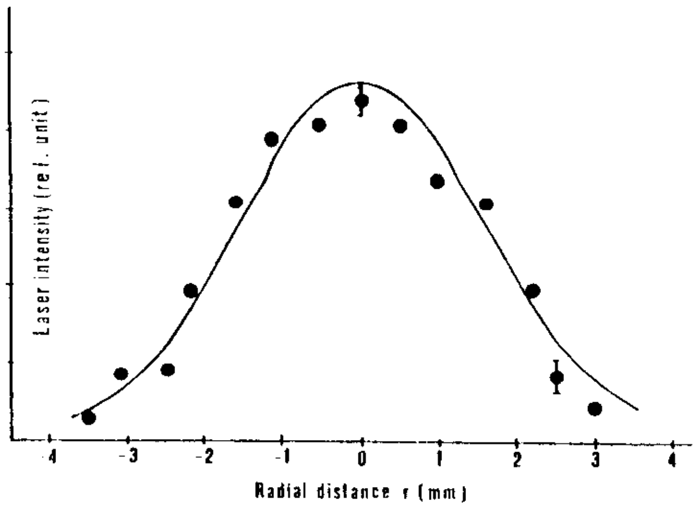

Fig. 2 - Near field laser intensity vs radial distance from the output beam center. M = 10, a - 0.3 mm. Solid line is our approximate analytical result.

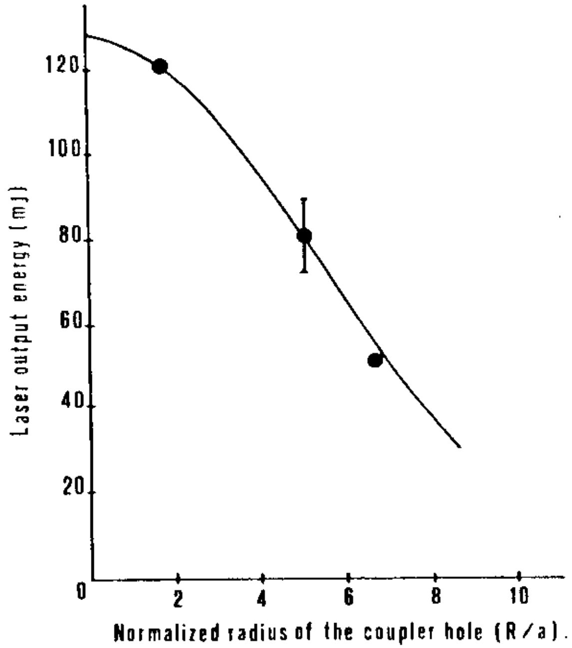

Fig. 3 - Laser output energy vs relative radius of coupler hole R/a. The working gas pressure is 4 atm.

FAR-FIELD DIVERGENCE MEASUREMENT

In order to evaluate the closeness of the laser spatial performances to the diffraction limit, the divergence of the laser radiation in the far field was measured by means of a fluorescent target* at the focus of a concave mirror of 10.6 m radius of curvature, and a video digital system composed of a standard TV camera, a 8-bit A/D converter, and a 128 K bytes frame memory. The objective assembly of the TV camera was modified, as shown in Fig. 1b, in order to obtain an image of the laser spot magnified by a factor of (40-80) on the monitor screen. The experimental results are shown in Fig. 4. The figure marker has a length

* Cr-doped Alumina, produced by Desmarguest & CiE, 2700 EUREUX, France

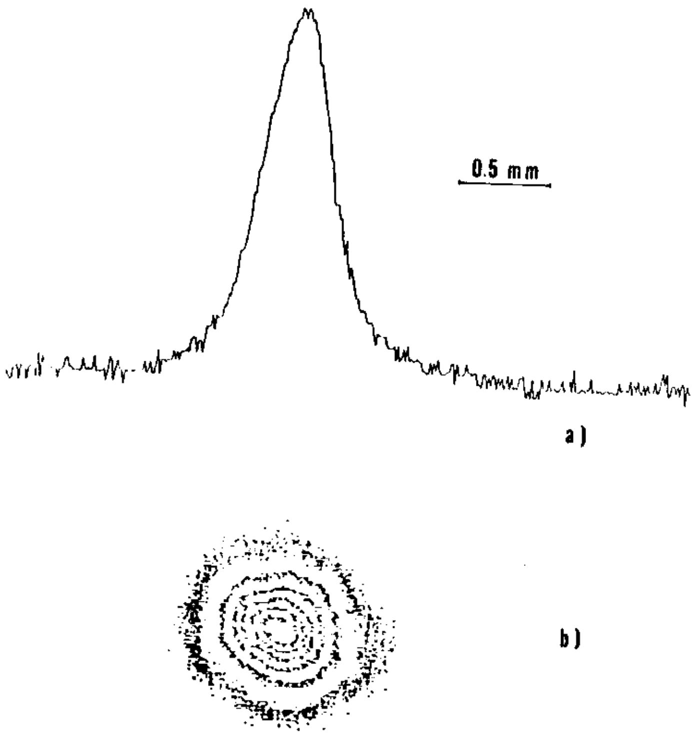

Fig. 4 - Laser intensity spatial profile (a), and intensity contour lines (b) at the focus of a concave mirror of 10.6 m curvature radius.

of 0.5 mm. This indicates a full angle beam divergence ($1/e^2$ intensity points) of ~ 0.15 mrad which is roughly consistent with the estimate of 0.13 mrad using a burn pattern on the copper surface at the same focus. The laser spatial profile in the far field has a good two-dimensional symmetry (Fig. 4b). During these measurements, the diameter of the laser output coupler hole was 1 mm, and the laser pulse energy was about 100 mJ with a pulse width of ~ 90 ns (FWHM). Some attenuators were used to reduce the laser energy so as to avoid the fluorescence intensity saturation of the target. A paper concerning the detailed description of such a measurement is in preparation.

MODE EVOLUTION TIME MEASUREMENT

We further investigated the temporal and spatial behavior of the mode in the SFUR configuration. The laser beam in the far-field could be resolved spatially into different components which have different divergences. If the steady state is not reached for the mode evolution, we expect that the time histories of these components may have different onset times, as explained in [8], because they have experienced several passes inside the cavity before being coupled out. The experimental configuration is shown in Fig. 1c. The time evolutions of the different beam components were observed by a pinhole (0.4 mm diameter) scanned along a direction perpendicular to its optical axis at the focus of the totally reflective concave mirror with a curvature radius of 17 m. Figure 5 gives the time histories of (a) d = 0 mm (at the center of the laser spot), (b) d = 0.25 mm, (c) d = 0.5 mm, where d is the perpendicular pinhole displacement from the optical axis. It can be seen that the three waveforms have almost the same onset time and pulsewidth (FWHM ~ 90 ns).

Consequently, we can deduce that one round trip is sufficient for the mode evolution to reach the steady state. Considering that the diameter of the laser spots is ~ 1.2 mm, our measurement resolution is rather limited by the scan pinhole diameter of 0.4 mm. In spite of this the above result is still basically consistent with the numerical

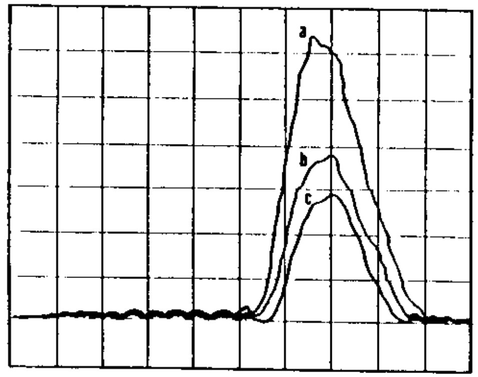

Fig. 5 - Time histories of laser beams observed at (a) 0 mm (the center of optical axis), (b) 0.25 mm; (c) 0.5 mm from the optical axis at the focus of a concave mirror of focal lenght 8.5 m. Horizontal 50 ns/div.

result that a steady state is established after just one round trip [9]. As a matter of fact, the far-field full angle divergence of 0.15 mrad realized in our experiments is near the diffraction limited value of 0.125 mrad calculated from 1.22 (λ/Ma). This means that the laser beam can be angularly demagnified near the diffraction limit in the SFUR after only one or two round trips.

THE INFLUENCE OF THE INTRACAVITY SPATIAL FILTER

From a geometrical point of view, it can be easily understood that for a confocal negative-branch unstable cavity with a high gain medium, the laser beam quality may be improved by placing a spatial filter with a small hole of radius A at the common focal point of the two cavity mirrors. In fact, in this case, the presence of a strong spatial filter aperture completely dominates the diffractive mode structure formation process. The laser beam in the far field can be approximately considered to be the image of the small hole, and its divergence depends on $2A/f_1$ to a great extent. Hence, the laser beam divergence in the far field will decrease with reducing the small hole size until it reaches the diffraction limit of 1.22 (λ/MA) which corresponds to the SFUR case. In fact, after substituting $M = |f_1/f_2|$ and $A = \sqrt{0.61 \cdot \lambda \cdot f_2}$ into the diffraction angle $1.22(\lambda/MA)$, we obtain $1.22(\lambda/MA) = 2A/f_1$. The change of the laser beam divergence with the small hole size is demonstrated in Fig. 6: all the laser divergences, except that of the 0.6 mm hole diameter, were estimated by the burn patterns at the focus of a concave mirror of curvature radius 10.6 m.

From a practical point of view, another important feature of a spatial filter aperture placed at the intracavity focus is that it can directly reduce the aberration sensitivity of an unstable cavity, defined as a measure of the transverse eigenmodes phasal response to an applied intracavity phase aberration source. As pointed out in Ref. [7], the aberration sensitivity decreases to unity as the spatial filter aperture size is decreased

DISCUSSION

As far as we know, this is the first time that the hard aperture SFUR configuration has been successfully applied to a discharge excimer

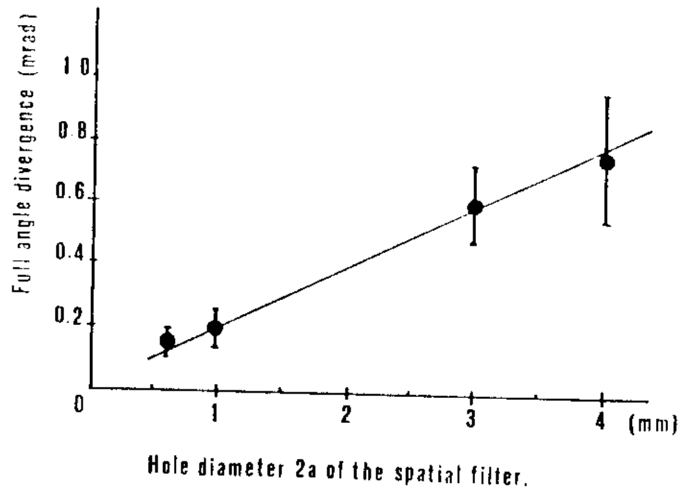

Fig. 6 - Far-field laser beam divergence vs the hole diameter of the spatial filter located at the common focus of the two cavity mirrors in the confocal negative branch unstable resonator depicted in Fig. 1a.

laser. The experimental results show many interesting points: the simplicity of the design; the high extraction efficiency; the good mode control ability; the good laser beam spatial profile which has nearly diffraction-limited, far-field divergence; the long term stability, and so on. However, as the mode volume is directly proportional to $(\lambda)^{1/2}$, it is not very large for excimer lasers, whose wavelengths are mostly in the UV-range, as compared to CO_2 lasers. On the other hand, the fast convergence to the fundamental transverse mode (Fig. 5) is a particularly attractive feature for an active medium with a very short population inversion lifetime and correspondingly high gain. In this sense, the SFUR configuration seems to be more suitable for excimer lasers than for YAG and CO_2 lasers.

We believe that the SFUR configuration for excimer lasers is more convenient for the devices which have small discharge cross sections, for example, of size ~ 1 cm. In this case, the filling factor of the mode volume can be very large.

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