High Optical Quality Laser Beams with confocal and non-confocal SFUR Schemes

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Abstract

Confocal and non-confocal negative branch unstable resonators with an intracavity spatial filter have been applied to a high-gain short-pulse UV preionized XeCl laser. The near- and far-field radiation characteristicis have been investigated in both configurations for different spatial filter diameter values. Laser beams of quite high brightness and with a regular intensity spatial profile have been obtained, in Particular laser beams of higher brightness have been obtained with non confocal schemes. A maximun beam brightness of 1.3×10^{14} $Wcm^{-2}Sr^{-1}$ has been achieved. A low sensitivity to mirror misalignments has also been observed.

Key Words: negative branch unstable resonators, SFUR.

§1. Introduction

Laser beams of high brightness are required to improve and widen the scientific and industrial applications of laser devices. Any effort in such direction must try to satisfy the following requirements. Firstly, the laser field mode volume must be made as large as possible in order to fill all the active volume and get high energy, high power laser beams. Secondly, laser beams spatially coherent across the entire beam cross section and with a smooth and regular intensity spatial profile must be generated to obtain an efficient laser energy transport and tight focalization spots. Finally, the laser beam parameters should not be very sensitive to mirror misalignments.

To satisf actory the previous requirements an extensive work has been devoted to the development and study of optical resonators, since the first appearance of laser devices. The optical quality of laser beam is mainly determined by the cavity transverse mode structure.

It was reported by Siegman[1] that, large mode volumes and high qulity laser beams can mainly be obtained by applying to laser devices unstable cavity configura-

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tions. The unstable resonator studies for lasers under quasi-continuous conditions are not very useful when such cavities are applied to high-gain short-pulse excimer lasers. In such lasors the upper level population lifetime is comparable with the time taken by a photon to travel along the resonator and the time for the development of a photon avalanche. An extensive analysis of the build up of modes in unstable resonators for high-gain short-pulse lasers has been presented in a series of papers by Anan'ev[2], by Zemskov et al.[3] and by Isaev ot al.[4]

The key concepts that emerge from their anlysis are that the unstable cavity magnification must be sufficiently large to enable a diffraction-limited mode to become the dominant mode in the resonator, in a time less than the time for the laser exhibiting gain. Moreover, the laser medium gain coefficient must be sufficiently small so that the lasing threshold is not reached before such a mode has had time to build up.

Positive branch unstable resonators have been generally applied to high power excimer oscillators to generate good-optical-quality and high-energy laser beams[5]. Up to now, the negative branch unstable resonators have not received much attention, since the presence inside the cavity of a focal point makes them unattractive for high power systems. However, a negative branch cavity called "Self-Filtering Unstable Resonators" (SFUR) was proposed a few years ago[6] and such resonator seems particularly suitable to the high-gain, short-pulse excimer lasers, to obtain diffraction limited laser beams with a regular intensity spatial profile[7,8,9].

To get larger mode volumes and shorter resonator lengths with respect to the SFUR scheme a non confocal SFUR called "Generalized Self Filtering Unstable Resonator" (G-SFUR) has been furtherly proposed[10,11,12]. The SFUR and G-SFUR working principles and main features will be presented in the next section.

It is the purpose of this paper to investigate and compare the performance of confocal and non-confocal SFUR schemes having the same cavity length and applied to a high-gain short-pulse UV preionized XeCl laser. The effect of the spatial filter size on the laser beam energy and brightness has been investigated in both configurations. The sensitivity to mirror misalignments of both schemes has also been tested.

§2. Basic Analysis

The SFUR is a confocal cavity with a filtering aperture FA at the confocal plane (Fig. 1). The main SFUR idea is to choose the filtering aperture radius a in order that a plane wave striking FA is focused by the shorter radiue concave mirror M_2 to an Airy disk of radius a. Let the Frenel number from a to M_2 less than 1, this means[6]:

$$a=(0.61\lambda f_2)^{1/2}, \tag{1}$$

Where λ is the laser wavelength and f_2 is the focal length of M_2. In such conditions, only the Airy disk propagates further beyond the aperture, is magnified and collimated by the mirror M_1. An exact Fourier transform relation connects the field distribution at FA and the new field distribution at the same plane after the field has been reflected by one of the mirrors (self imaging condition).

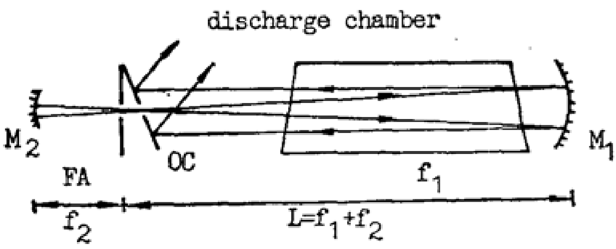

Fig. 1 Experimental set up of the confocal scheme; M_1 and M_2 concave mirrors; FA spatial filtering aperture of diameter $2a$; OC-output coupler

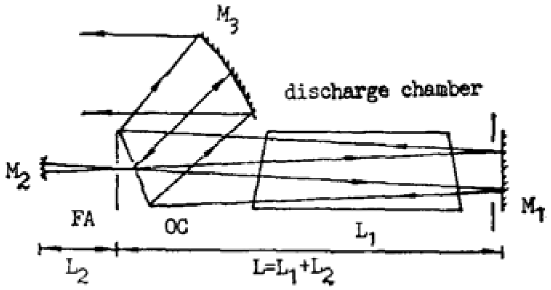

Fig. 2 Experimental set up of the nonconfocal scheme; M_1 plane mirror; M_2 concave mirror; FA spatial filtering aperture of diameter $2a$; OC output coupler; M_3 collimating mirror

It comes out that the Airy disk choice removes the hot focal point since the diffraction from the filtering aperture contrasts the focusing action of th M_2 mirror. Such a choice allows also, a fast establishment of the steady state laser field, since it minimizes the number of round trips needed to establish a laser mode starting from incoherent fluorescence. Moreover, a smooth field profile, completely free of modulations, can be obtained with such resonator scheme[7,8]. However, the main drawback of this configuration is due to the dependence of the laser beam mode volume on the magnification value M and on the radiation wavelength. In fact, the output beam reaches zero amplitude at a radius $R \simeq 1.5|M|(0.61 f_2 \lambda)^{1/2}$ and, when the SFUR is applied to short-pulse excimer lasers quite small mode volumes can be achieved. This arises firstly from the explicit dependence of the R value on laser wavelength. Secondly, the excimer laser pulse duration limits resonator length, maximum magnification value and then laser beam cross section. To overcome this problem partially a Generalized Self Filtering Unstable Resonator (G-SFUR) has been proposed[10]. The G-SFUR is a non-confocal resonator made up by a plane mirror, a concave mirror and an intracavity field limiting aperture (Fig. 2). In such scheme the filtering aperture size and its location with respect to both mirrors, are chosen in order to get a configuration having the same features of SFUR.

In particular, the FA location and therefore its distance L_1 from M_1 and its distance L_2 from M_2 must be determined by requirementing of that the image plane of the pinhole, after one round trip, corresponds to the pinhole plane itself

$$L_2 = f_2(1 + f_2/2L_1) \tag{2}$$

Secondly, the FA radius must be chosen in order to cut off the oscillations of the eigenmode TEM_{00} in the short part of the cavity, so:

$$a=[L_2\lambda(1-L_2/2f_2)]^{1/2}. \tag{3}$$

The magnification is then·

$$M=-\frac{L_1}{L_2}\frac{1}{1-L_2/(2f_2)} \tag{4}$$

From the previous relations it comes out that the G-SFUR magnification can be simply varied by varying the L_1 flat mirror distance from FA. Moreover, from equations (2) and (4) it comes out that for $L_1 \gg f_2$, the G-SFUR scheme allows to get M values about twice larger than the M values obtained with a SFUR scheme having the same less curved mirror and resonator length.

Since in the G-SFUR cavity the wave fronts of the modes are curved, the output beam extracted near the pinhole screen can be collimated by a mirror M_3 having focal length[10]

$$f_3=d-\frac{2L_2(1-L_2/2f_2)}{1-L_2/f_2} \tag{5}$$

where d is the distance between FA and M_3.

§3. Experimental Apparatus

The UV-preionized discharge excited XeCl laser used in this experiment has been realized in Italy. The discharge is of the capacitor charge transfer type, with a primary and secondary capacitance of 150 nF and 25 nF, respectively. The laser chamber is made of a 68 cm long, commercially available PVC tube which contains the electrode structure. The discharge electrodes of 50 cm long, and 5 cm wide are set at a distance of 2 cm. The UV preionization is provided by a spark array rod located on one side of the electrode structure. The preionization rod is driven by a capacitor (C_p=10 nF) which is switched simultaneously with the primary capacitor, by a spark gap. The electrode assembly cross section and the schematic electrical diagram of the laser system are shown in Fig. 3. The laser chamber sealed with Brewster angle windows is about 80 cm long. A standard gas mixture (1% HCl, 2.1% He, 1.3% Xe, 96.5% Ne) at a total pressure of 400 kPa has been used.

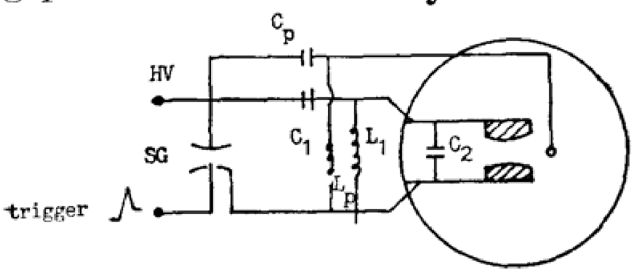

Fig. 3 Electrode assembly cross-section and schematic electrical diagram of the laser system

With a plane parallel optical resonator, made up of an aluminized silica reflector and an UV grade silica output coupler, an output beam (1.1×2) cm^2 of 250 mJ and 32 ns duration (FWHM), has been obtained at the highest value of the breakdown voltage of the internal capacitors (V_b=43 kV). A laser extraction energy density of

$2.3\,mJ/cm^3$ has been then achieved.

A schematic set-up of the negative-branch confocal unstable configuration is shown in Fig. 1. M_1 and M_2 are concave mirrors of focal length $f_1=100$ cm and $f_2=10$ cm respectively, then, the cavity magnification is $|M|=10$. FA is the filtering aperture, made of a 25 μm thick stainless steel disc with a drilled hole of radius a located at the confocal plane. A plane mirror OC set neat FA has been used as laser beam output coupler. To fulfil the "SFUR self-filtering condition", the spatial filter diameter must be set at $2a=0.27$ mm under our experimental conditions.

In order to realize a G-SFUR having the same cavity length and the same M_2 mirror as in the SFUR scheme previously described, the values of L_1 and L_2 have been set at 99.5 cm and at 10.5 cm respectively, in accordance with Eq. (2). Moreover, a filtering aperture of diameter $2a=0.25$ mm has been used, as required by Eq. (3). A cavity with a magnification $|M|=19.9$ has been then realized. This value is about twice larger than the M value of the corresponding confocal scheme. To collimate the laser output beam, a concave mirror M_3 of 239 cm focal length, placed at about 39.5 cm from OC has been used, as indicated by Eq. (5). A schematic set-up is shown in Fig. 2.

§4. Experimental Results and Discussion

By applying the SFUR scheme to our XeCl laser, a laser beam of 11.5 mJ and of 22 ns duration (FWHM) has been obtaind at the highest value of the breakdown voltage ($V_b=43$ kV), A laser energy density of $1.8\,mJ/cm^3$ has been then eotracted.

The far field beam divergence was determined by measuring the laser beam diameter at the focal plane of a 5 m lens. It has been found from the experimental results that more than 85% of the far field beam energy is comprised in a spot corresponding to a full angle beam divergence $\vartheta=0.28$ mrad. Therefore, a nearly diffraction limited laser beam has been obtained with the SFUR scheme. In fact, ϑ is only 1.5 times larger than the diffraction limited value $\theta d=2.44\ \lambda/3a|M|$, Thus a beam brightness of about $7\times10^{13}\ Wcm^{-2}\ Sr^{-1}$ has been achieved.

With the G-SFUR scheme applied to the same XeCl laser, a beam of 21 mJ and of 18 ns duration (FWHM) has been obtained at $V_b=43$ kV.

By measuring the collimated laser beam diameter at the focal plane of a 5 m lens, a full angle beam divergence of 0.15 mrad has been obtained. Since a laser beam diameter of 7.3 mm was measured on M_3, the divergence is 1.6 times larger than the diffraction limited value of 0.1 mrad. The above mentioned divergence value depends on the collimating mirror position. It is convenient to find out the G-SFUR divergence value corresponding to the beam diameter on the output coupler mirror OC, to better compare the SFUR and G–SFUR performance parameters. A beam diameter of 6.3 mm has been measured on the OC mirror, then a beam divergence and brightness of 0.19 mrad and 1.3×10^{14} $Wcm^{-2}Sr^{-1}$ respectively have been achieved with the G–SFUR configuration. Moreover, a laser output energy density of about 2.2 mJ/cm^3 has been achieved. Such extraction energy density value is very close to the value obtained with a plane–parallel cavity scheme.

From the experimental results just described, we observed a shorter pulse duration of the laser beam obtained with the G–SFUR configuration, with respect to the SFUR laser beam time length. This would be due to the higher magnification value of the G–SFUR scheme and so to the higher mode losses of such cavity, which are determined by $(1-1/M^2)$. Therefore, the gain factor of the active medium is greater than the threshold gain value for a shorter time in the last configuration[7].

We have observed that a higher energy density has been extracted and a beam brightness of 50% larger has been achieved with the G–SFUR scheme.

The laser energy E and pulse width Δt as a function of the breakdown voltage have also been measured in both resonators. The experimental results plotted on Fig. 4 and Fig. 5 show a nearly equal behaviour of E_0 and Δt versus V_b in both cavities.

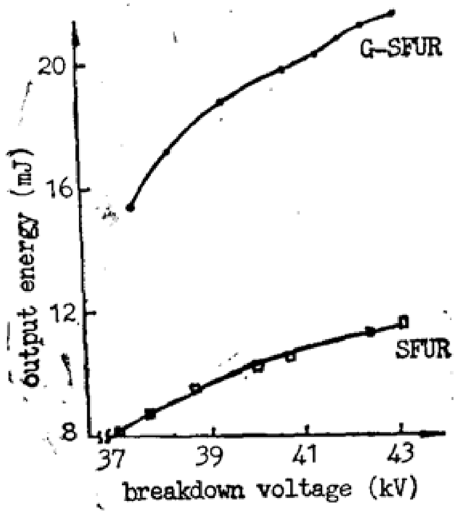

Fig. 4 Output energy as a function of the breakdown voltage for the SFUR (□) and for the G–SFUR (•) schemes Breakdown Voltage (kV) Output Energy (mJ)

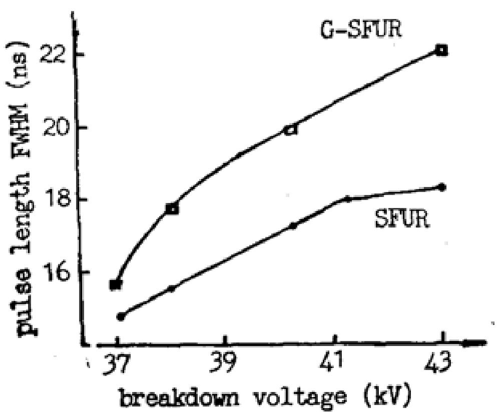

Fig. 5 Pulse width (FWHM) as a function of the breakdown voltage for the SFUR (□) and for the G–SFUR (•) schemes

It has also been observed that the sensitivity to mirror misalignmentsis nearly the same in both configurations. The experimental measurements of the normalized output energy as a function of the mirror tilting angle are shown in Fig. 6. It turns out that the value of the tilting angle which halves the normalized output energy is about 1.5 mrad for both cavities.

Therefore, it has been found that in accordance with theory, the G–SFUR maintains the excellent properties of SFUR, like high transverse mode discrimination, fast establishment of nearly diffraction limited output beams, low sensitivity to mirror misalignments, but allows to have larger mode volumes with shorter resonator lengths, with respect to th SFUR scheme.

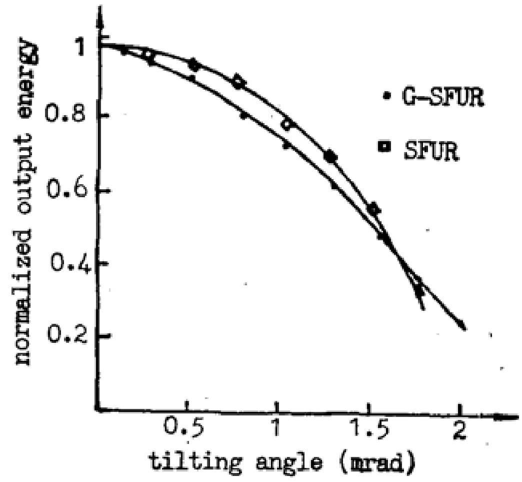

Fig. 6 Normalized output energy as a function of the tilting angle for the SFUR (□) And for the G-SFUR (•) schemes

It is important to observe that with such resonator configurations, larger mode volumes can also be obtained by increasing the filtering aperture radius beyond the value required by the "self-filtering condition". Therefore, the FA radius, a, has been varied and its effect on the output beam energy and divergence has been investigated in the confocal and in the non-confocal configuration.

Three filtering apertures with diameters of 0.5, 0.7 and 0.9 mm respectively have been tested in the confocal scheme.

In the non-confocal scheme, three filtering apertures with diameters of 0.3, 0.4 and 0.5 mm respectively have been tested and laser beams with diameters of 7.5, 9 and 11 mm respectively, have been measured on the OC mirror.

In both configurations, the laser output beams show a regular intensity spatial profile even at a value larger than those required by the "self-filtering conditiont". This is a peculiar property of such negative branch unstabie resonators. It is well known that with positive branch unstable cavities, the intensity radial variation of the output beam shows, instead, a characteristic ring pattern which arises from diffraction effects.

The effect of the filtering aperture size on the output laser beam energy and

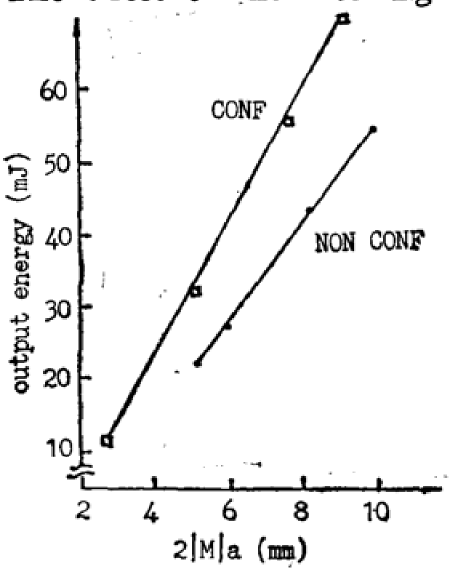

Fig. 7 Output laser beam energy versus $2|M|a$ for the confocal (□) and for the non-confocal (•) schemes

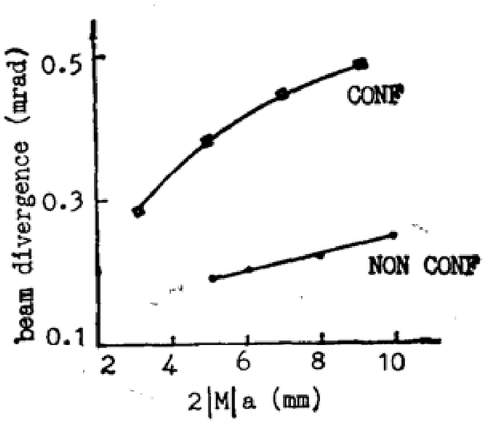

Fig. 8 Laser beam divergence versus $2|M|a$ for the confocal (□) and for non-cocfocal (•) schemes

divergence, is shown in Fig. 7 and 8 for the confocal and non-confocal configuration respectively. The experimental results plotted as a function of $2|M|$ a show in both schemes a linear growth of the output energy as the laser beam cross section increasing (Fig. 7). But, laser beams of higher energy are obtained with the confocal scheme at a given $2|M|a$ value. This would be due to the lower mode losses and to the higher feedback signal (i.e. higher a value) of the last configuration.

The laser beam divergence does also grow as the a value and then the beam diameter are increased. A faster rise of the laser beam divergence versus $2|M|a$ is observed in the confocal scheme. Since the filtering aperture size affects strongly the mode selection in both schemes, we observed that laser beams of higher energy, but of lower optical quality, were obtained at larger a values. It is important to point out that the number of round trips to get a diffraction-limited beam starting from spontaneous emissions, gets larger by increasing the a value, beyond the value required by the "self-filering condition", as it comes out from simple geometrical optics considerations[3,7]. Fig. 9 gives the beam brightness versus $2|M|a$. In both configurations the beam brightness slows down by increasing the a values. Neverthless, with the non confocal scheme a beam of quite high brightness has been obtained at the largest $2|M|a$ value investigated.

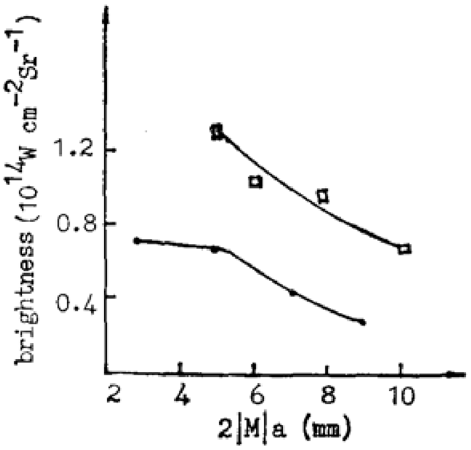

Fig. 9 Laser beam brightness versus $2|M|a$ for the confocal (□) and non-confocal (•) schemes

It is important to point out that, in both schemes, not hot spots have been observed at the resonator focal plane, at the highest excitation rates and up to a repetition rate of 1Hz. Moreover, the radius a of FA after more than 1000 shots was unchanged in both cavities.

§5. Conclusions

Confocal and non-confocal negative branch unstable resonators with an intracavity spatial filter have been applied to a high-gain short-pulse UV-preionized XeCl laser. By setting the spatial filter diameter equal to the value required by the SFUR and the G-SFUR "self filtering condition" respectively, nearly diffraction limited beams have been obtaind with both schemes. But, a laser beam with a higher brightness has been achieved with the G-SFUR configuration. In fact, in accordance with theory, the G-SFUR maintains the excellent properties of SFUR, but allows to have larger mode volumes with shorter resonator lengths with respect to SFUR.

By increasing in both configurations the spatial filter diameter beyond the value required by the "self-filtering condition" respectively, laser beams of higher energy, but of relatively lower optical quality, have been obtained. In fact, the spatial filter size affects strongly the mode selection in both schemes.

Neverthless, it is important to point out that laser beams of quite high brightness and with a regular intensity spatial prefile can be obtained by applying such resonators to high-gain short-pulse excime lasers.

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具有高光学质量共焦和非共焦自滤波非稳腔的激光束

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提 要

具有腔内滤光器的共焦和非共焦负支非稳腔应用于高增益、短脉冲紫外予电离氯化氙激光器，在上述两种腔结构，研究了各种空间滤光器条件下的近场和远场辐射特性，获得了有规则强度空间剖面的高亮度激光束，特别是非共焦机构，最大束亮度达 1.3×10^{14} 瓦·厘米平方·立体角，并且观察到，这种腔结构对于失调的低灵敏度。

关键词：负支非稳腔，自滤波非稳腔。