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SUPERSONIC FLOW LOW TEMPERATURE ELECTRONIC TRANSITION EXCIMER LASERS

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Résumé.— Des émissions laser ultraviolettes de grande puissance ont été obtenues à partir de transitions électroniques d'excimères au moyen du dispositif de l'I.M.F.M. où un milieu gazeux en écoulement supersonique à très basse température et densité élevée est excité par un faisceau d'électrons ou une décharge stabilisée par faisceau d'électrons ($\rho \leq 2$ amagats, $T \approx 70 - 150$ K). Les effets d'un fort refroidissement et d'une très grande vitesse d'écoulement sur les caractéristiques de plusieurs systèmes laser U.V. et visibles (XeF^* , XeCl^* , Ne^+ , F^*) sont décrits. Les effets d'un fort refroidissement du milieu actif sur d'autres systèmes intéressants en tant que lasers potentiels, sont également décrits et notamment la mise en évidence d'un très fort accroissement de l'intensité de fluorescence dans les domaines de l'U.V. et du visible de transitions de trimers (Kr_2F^* , Xe_2Cl^* , Kr_2Cl^*). Des résultats expérimentaux obtenus à l'I.M.F.M. et concernant la stabilité des décharges en écoulement supersonique à haute densité et les caractéristiques optiques du milieu en écoulement après excitation, étudiées par interférométrie, sont également présentés. Les possibilités des systèmes à densité élevée et écoulement à grande vitesse sont discutées dans le cadre du développement des futurs systèmes laser à excimères de puissance moyenne élevée.

Abstract.— High power pulsed ultraviolet excimer laser emissions have been achieved with the high density and very low temperature supersonic flow-electron beam excitation and supersonic flow - electron beam stabilized discharge excitation devices developed at I.M.F.M. ($\rho \leq 2$ amagats, $T \approx 70 - 150$ K). Experimental results are given for effects of strong cooling and very high speed and high density flow on lasing characteristics of several U.V. and visible laser systems (XeF^* , XeCl^* , Ne^+ , F^*). Effects of strong cooling on other excimer systems and noticeably strong enhancement of fluorescence efficiency for several trimers (Kr_2F^* , Xe_2Cl^* , Kr_2Cl^*), very attractive as potential visible high efficiency lasers, are described. Experimental results on fluid dynamics of these supersonic flow U.V. and visible lasers, noticeably discharge stability, and flowing medium behavior following excitation, as recorded by interferometry, are presented. Possibilities of very high speed flow, high density systems are discussed with the aim to consider development of future high average power excimer lasers.

INTRODUCTION

Excimer lasers promise the availability of high average power coherent sources in the ultraviolet and visible regions of the spectrum.

Potential applications of such laser systems are important in particular in the energetic field^{(1),(2)}. However in scaling these lasers to high average power, challenging problems are encountered in source of excitation, molecular kinetics and active medium homogeneity. The difficulty of this last problem is increased by the high gas density^{(3),(4),(5)} and short wavelength⁽⁶⁾ of these systems.

Fluid mechanic techniques associated to electrical excitation are of high interest to achieve such high average power U.V. and visible lasers through electronic transitions of molecules⁽⁷⁾

and to maintain a good medium homogeneity in the same way as the well known infrared vibrational flow lasers^{(3),(8),(9)}. Very recently up to 220 Watts average power has thus been extracted in the U.V. from a high repetition rate subsonic flow excimer laser at GTE -Sylvania by Fahlen⁽¹⁰⁾ and possibility of very high repetition rate has been demonstrated by R.C. Sze at Los Alamos⁽¹¹⁾ and C.P. Wang at Aerospace Corporation⁽¹²⁾ and J.L. Miller at Lawrence Livermore Laboratories⁽⁷⁾.

In the case of electronic transition molecular lasers and more particularly with high density active medium, strong cooling of the working medium may tend on the one hand to lower the excited species quenching and absorption losses and, on the other hand to increase the rate and the branching ratio of useful specific reactions and more generally the gain of the laser

Cooling the gas by means of a supersonic expansion could moreover lead to C.W. or very high repetition rate laser systems as the heat and waste products are very rapidly carried away by the supersonic flow together with the aerodynamic disturbances induced by energy deposition.

Associated with supersonic flow and adiabatic expansion which permits to reach temperatures not easily achievable with thermal exchangers, the use of a high energy electron beam stabilized discharge to excite the gas mixture could allow development of high average power high efficiency excimer laser systems.

The aim of this paper is to present the characteristics of several quasi-continuous laser emissions achieved on several excimer systems in the ultraviolet range with supersonic flow - electron beam excitation and supersonic flow - electron beam stabilized discharge excitation devices developed at I.M.F.M.

Some results on excimer fluorescence enhancement following strong cooling and fluid dynamics of excimer lasers active medium are also presented.

EXPERIMENTAL SET-UP

The basic apparatus has been described in details elsewhere^{(13),(14)}. It consists mainly of a small pulsed blowdown device of the Ludwig tube type coupled to a medium intensity cold cathode electron gun and a discharge bank (sustainer).

The Ludwig tube (16 x 3.8 cm² cross section, 50 cm length) feeds, through a supersonic nozzle, a constant area channel (16 x 3 cm²) associated to the cold cathode electron gun and flush mounted discharge electrodes as shown on Fig. 1. Minimum length supersonic nozzles and a screen nozzle are used matching the flow to $M = 1.75, 2.5, 3$ and 2.1 respectively in the constant area part of the

channel.

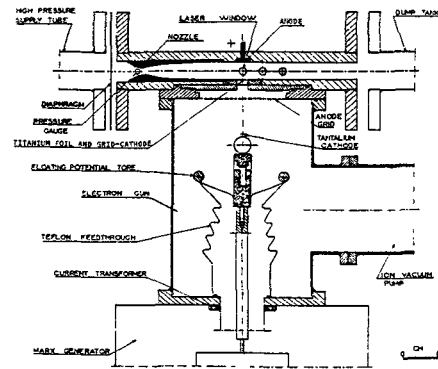


Fig.1 Cross-sectional view of the test section and electron gun.

The test section was constructed either in welded aluminium for e-beam experiments or in fiber glass and epoxy for e-beam stabilized discharge experiments. The calculated values of pressure, density, temperature and gas celerity for the first stationary flow taking into account the instationary phenomena in the supply tube are given on Table 1 for an initial supply tube pressure of 7.5 atmospheres of argon.

Typical duration of stationary flow is 2ms for argon. A foil (20 x 140 mm) of 1 mil of Titanium, transparent to the high energy electrons, permits the electron beam to excite the active medium in supersonic flow. This foil is either flush mounted in the bottom wall of the channel or located slightly back below a flush mounted high transparency tungstene grid. Particular care has been taken for the alignment of the different parts of the test section in order to minimize aerodynamic disturbances.

When experiments are performed with an e-beam sustained discharge, the voltage is applied between a copper electrode carefully flush mounted in the upper wall of the channel and the tungstene grid. The electron beam is generated by a home made cold cathode electron gun energized by a P.I.M X 31 Marx generator (300 KV - 1500 J). The e-beam cur-

Table 1 - Calculated flow parameters in the test section for the first stationary flow ;
initial supply tube pressure is 7,5 atm (argon)

Mach Number	Nozzle	P(Atm)	$\rho(10^{19} \text{ cm}^{-3})$	T(K)	$U(\text{ms}^{-1})$
1,75	2 D	0.81	4.86	119.7	357.9
2.5	2 D	0.33	2.85	83.7	427.6
3	2 D	0.19	2.03	66.6	457.8
2.1	Screen	0.43	3.18	99.2	389.9

rent density after the titanium foil can be varied between 5 A cm^{-2} for $2 \mu\text{s}$ and 20 A cm^{-2} for $0.5 \mu\text{s}$.

A low inductance sustainer bank ($0.5 \mu\text{F}$ - 15 KV) triggered by a spark gap or an ignitron permit to apply an electric field of up to 2 KV cm^{-1} to the e-beam preionized gas mixture. Sustainer current density j_D is comprised between 30 and 200 A cm^{-2} . Discharge and e-gun are generally fired when the flow is stationary.

Interferometric grade windows and hard coating multidielctric mirrors are integrated in the channel side walls. Large dimension interferometric grade windows $80 \times 30 \text{ mm}^2$ may be flush mounted in the side walls of the test section allowing to record by interferometry mapping the density in all the channel including the boundary layers.

Experiments are also performed with this device without flow at room temperature with the same sample of gas mixture at the same density in order to obtain a direct comparison between low temperature, flow and room temperature, no flow, laser performances.

DIAGNOSTICS

The measured parameters consists mainly in :

- routine control of Marx generator and supersonic flow,
- discharge current and voltage by means of current transformer and a resistive divider respectively,

- supersonic flow and static gas mixture density map and their space and time variation following e-beam or e-beam sustained discharge by means of a large field Michelson interferometer using an home made pulsed ion laser source (streak and snapshot photographs),
- time variation of laser and fluorescence intensities by means of filtered PMT and photodiodes. The signals are recorded either directly on oscilloscopes or through the use of high speed transient digitizers (20 MHz bandwidth) and a Digital PDP 11 V03 minicomputer,
- time integrated spectral distribution of laser and fluorescence emissions by means of low and high resolution grating spectrographs. An home made optical multichannel analyser associated to the PDP 11 V03 minicomputer permits moreover to measure spectral energy distributions,
- total extracted optical energy by means of ED 100 and ED 200 Gentech joulemeters.

EXPERIMENTAL RESULTS

Laser emissions

The described device has allowed the generation of several high power quasi CW ultraviolet and visible laser emissions from $\text{XeF}^{(15)}$, $\text{XeCl}^{(16)}$, ionic $\text{Ne II}^{(17)}$ and atomic $\text{F}^*^{(18)}$. On table 2 are summarized the experimental results obtained at I.M.F.M.

Table 2 - Main characteristics of supersonic flow high density and low temperature lasers achieved at IMFM

Gas mixture	Wavelength	Assignment	Specific energy and efficiency	Excitation
Ne/Xe/NF ₃	many lines ≈ 3500 Å	XeF (B → X)	≈ 0.05 j/ℓ in 0.4 μs	e.beam
Ne/NF ₃	3378, 23, 3481, 95 Å	Ne II		e.beam
Ne/Xe/HCl	Three lines 3079, 3082, 3084 Å	XeCl(B → X)	1.0 j/ℓ in 0.5 μs η = 2.5 %	e.beam e.b. + discharge
Ar/Xe/HCl	Two lines 3079, 3082 Å	XeCl(B → X)		e.beam
He/NF ₃	7130, 7310, 7552 Å	F I		e.beam

The present device has in particular permitted to obtain the first supersonic flow excimer laser (XeF* λ = 350 nm) and to achieve laser specific energy and power of 1 j/ℓ and 2 MW/ℓ respectively with over 2.5 % intrinsic efficiency from XeCl (λ ≈ 308 nm) at very low temperature in supersonic flow. These values are noticeably higher than the room temperature no flow one. It seems that with conditions of low temperature and high density it would be possible to extract specific laser energy as high as 10 - 15 j/ℓ at 3080 Å.

The present device has also permitted very recently to achieve, for the first time, lasing on an excimer with an e-beam stabilized discharge in a supersonic flow and these last results are presented hereafter with some detail.

The experimental conditions where M = 1.75, T ≈ 120 K and ρ = 1.8 amagat. It is noteworthy that for conditions where e-beam excitation alone did not permitted to reach threshold for lasing addition of an electric field as low as 0.3 KV/cm permitted to achieve lasing. Experiments with higher electron beam current density showed that addition of the discharge strongly enhanced power and energy laser output for unsaturated gain conditions. On Fig. 2 are shown typical waveforms of

XeCl laser power (λ = 308 nm) obtained for low temperature supersonic flow conditions. Fig. 2a corresponds to electron beam excitation alone (j_{e.b.} = 4 A cm⁻² - 240 KV) constant for all results of the present paper while Fig. 2b corresponds to an e-beam sustained discharge (V_{capacitor} = 5 KV, E_D = 0.6 KV cm⁻¹, j_D = 130 A.cm⁻²). All the laser signals were recorded for a resonant cavity with 0.1 % and 5 % transmission mirrors at 308 nm and 1.8 amagat Ne/Xe/HCl (1000/25/1) mixture at T = 120 K (M = 1.75). Attenuation and detector sensibility were the same for the two laser signals. It is to note the strong increase of laser power and energy and also the earlier starting of laser emission when the discharge was added to e-beam excitation.

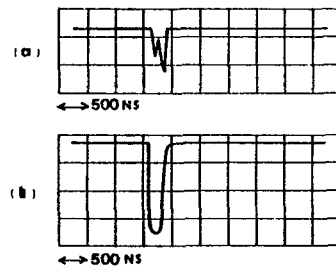


Fig.2 Typical laser waveforms from supersonic flow XeCl laser. a) e-beam excitation, b) e-beam sustained discharge excitation.

On Fig. 3 is shown the time dependant discharge current obtained for the supersonic flow and excitation conditions corresponding to Fig. 2. One can observe that it is possible to achieve conditions of stable discharge during 300-400 ns for such conditions of flow, temperature and density.

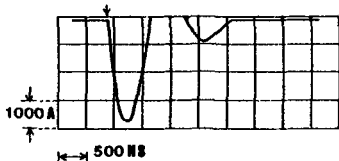


Fig.3 Discharge current time history for supersonic flow XeCl laser.

On Fig. 4 is shown the measured discharge current as a function of capacitor voltage for either supersonic flow and no flow conditions. On this figure one can observe the limit of possible capacitor voltage due to arcing during the e-beam excitation.

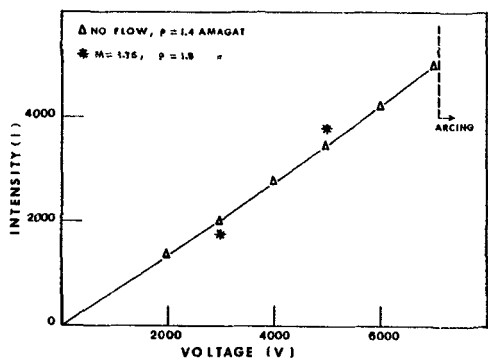


Fig.4 Measured discharge current as a function of capacitor voltage for e-beam sustained discharge excitation of Ne/Xe/HCl (1000/25/1). $j_{e.b.} = 3 \text{ Acm}^{-2} - 0.5 \mu\text{s}$.

On Fig.5 is shown the measured peak power added to unit volume of active medium by the discharge taking into account measured electrode voltage and current time variations. For these experimental conditions the e-beam power absorbed by the medium was about 20 MW/l constant during 500 ns.

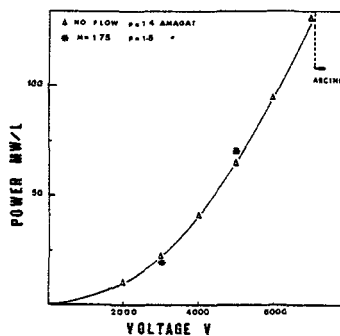


Fig.5 Measured peak power added by the discharge in an e-beam sustained discharge XeCl laser.

One observe that it is possible to add, by the use of stable discharge, 7 times more power to the medium than with e-beam alone in these conditions. The discharge duration was 400 ns and lasing duration was 300 - 350 ns.

Fig. 6 shows the variation of laser power and energy in function of capacitor voltage for either supersonic flow and no flow conditions and Ne/Xe/HCl (1000/25/1) mixture not optimized for discharge.

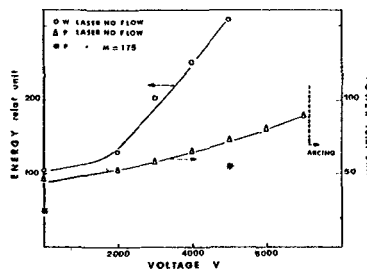


Fig.6 Measured extracted laser energy and power for e-beam sustained discharge XeCl laser.

These resultsetheir at low or room temperature have strong implications for the development of high average power ultraviolet excimer lasers because they demonstrates the possibility to add efficiently more energy to the gas mixture in supersonic flow by means of the discharge of an e-beam stabilized discharge than by the e-beam alone. This is important because strong technological difficulties limit the present state-of-the art average power achievable with high energy high repetition rate electron beams ; these limitations are mainly due

Table 3 - Main uv and visible fluorescence intensities enhancements observed in supersonic flow high density and low temperature e-beam excited gas mixtures

Gas mixture	Wavelength	Assignment	I_T / I_{300K}
Ar/Xe/CO ₂ (5200 - 5600 ; 3200 Å	XeO _{1S} → XeO _{1D}	50 at 120 K
Ar/Xe/N ₂ O (300 at 80 K
Ar/Xe/O ₂ (XeO _{1S} → XeO _{3P}	id
Ar/Xe	3295 Å	Ar ⁺ Xe → ArXe ⁺	10 at 120 K ; 30 at 80 K
Ar/COS	2985 Å - 3560 Å	?	Very high at 120 and 80 K
Ar/Xe/NF ₃	2600 Å	XeF* (D → A)	≈ 1,5 to 2 at 120 and 80 K
	3500 Å	XeF* (B → X)	≈ 1 at 120 and 80 K
	3805 Å	ArXeF* → ArXeF (?)	Very high at 120 and 80 K
	4700 Å	XeF* (C → A)	≈ 1,5 to 2 at 120 K
Ar/Kr/NF ₃	2500 Å	KrF* (B → X)	≈ 1 at 120 K
	4100 Å	Kr ₂ F* → Kr ₂ F	High at 80 and 120 K
Ar/Xe/HCl	3080 Å	XeCl* (B → X)	≈ 1 at 120 K
	3260 Å	ArXeCl* → ArXeCl (?)	Very high at 120 K
	3500 Å	XeCl* (C → A)	1,5 at 120 K
	4800 Å	Xe ₂ Cl* → Xe ₂ Cl	High to 120 K
	5100 Å	Xe ₂ Cl* → Xe ₂ Cl (?)	Very high at 120 K
Ar/Kr/HCl	2220 Å	KrCl* (B → X)	≈ 1 at 120 K
	3300 Å	Kr ₂ Cl* → Kr ₂ Cl	High at 120 K

to electron gun foil heating and spark gap reliability.

FLUORESCENCE EFFICIENCY ENHANCEMENT OF EXCIMER SYSTEMS

Effect of a strong cooling on the fluorescence efficiency of numerous excimer systems have been investigated with the I.M.F.M. supersonic flow device. The main results of this investigation are summarized on table 3.

A strong enhancement of the fluorescence intensity, sometimes several orders of magnitude, has been observed on several of these systems, notably in the case of trimers (Kr₂F*, Xe₂Cl*, Kr₂Cl*) which are produced by three body reactions highly favored in conditions of high density and very low temperature.

These systems, when fluorescence efficiency is relatively high, are very attractive as potential visible high efficiency lasers. It is noteworthy that lasing has been achieved very recently in an U.S. Lab. on the Xe₂Cl* continuum near 500 nm⁽¹⁹⁾. As an exemple the Fig. 7 shows microdensitometer

traces of fluorescence spectral energy distribution in the case of an Ar/Xe/HCl mixture excited at T = 120 K and T = 300 K respectively.

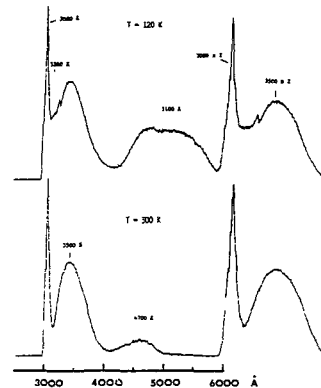


Fig. 7 Microdensitograms of fluorescence spectra. Ar/Xe/HCl (1000/29/1.5), e-beam excited.

GAS DYNAMICS

Through laser action in the ultraviolet and visible range from a high density supersonic flow has been demonstrated at I.M.F.M., study of aerodynamic losses, particularly density disturbances following gas dynamic phenomena, must be carefully undertaken in the frame of high power C.W. or pulsed high repetition rate ultraviolet or visible supersonic flow laser development. The general

questions interesting to answer for evaluation and control of gas dynamic phenomena involved in high density supersonic flow electronic transition lasers are the following ones.

- 1) what large density disturbances are tolerable to maintain good laser beam quality at so short wavelengths.
- 2) are these conditions achievable in a high density high speed flow (supersonic or subsonic).
- 3) what is the active medium behavior when it absorbs electron beam or discharge energy at high loading either without initial flow or in a high density supersonic flow.

The study of these questions is in progress at I.M.F.M. (20), (21) and hereafter are presented shortly, some preliminary experimental results obtained very recently at I.M.F.M.

We have obtained, in supersonic flow, density gradients $\Delta\rho/\rho$ of the order of 10^{-2} for 1 cm field at the center of the channel and this figure could be further decreased, probably by an order of magnitude by a better design of the channel. Even with the present design it has been possible to achieve laser beams where no difference appeared between flow and no flow intensity spatial variation.

Experimental investigations, by use of snapshot and streak interferometry, of density variations following energy deposition have been undertaken when an e-beam or an e-beam sustained discharge excited the gas mixture for typical excimer laser conditions.

Fig. 8 shows typical snapshot interferograms. One snapshot (Fig. 10a) shows density disturbances 50 μ s after firing without flow. The other snapshot (Fig. 10b) shows the density disturbances at the same time with supersonic flow ($M = 2.1$) for the same conditions of density ($\rho = 1$ amagat).

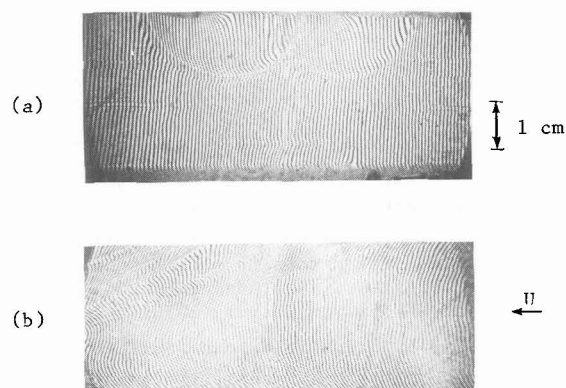


Fig. 8 Snapshot interferograms of neon excited by an e-beam sustained discharge : $V_{e.b.} = 210$ KV, $j_{e.b.} = 3$ A $\text{cm}^{-2} - 0.5$ μ s, $V_{\text{capacitor}} = 5$ KV, $j_D \approx 100$ A cm^{-2} , $\rho = 1$ amagat. (a) no initial flow ; (b) supersonic flow ($M = 2.1$). Pictures are taken 50 μ s after excitation.

The disturbances are in fact swept away by the very high speed flow permitting to reach conditions of good beam quality for high power high repetition rate lasers in the U.V. and visible at high loading.

CONCLUSION

The results presented here, without entering in the details of all the involved phenomena, show the ability to generate high power ultraviolet laser beams and strong fluorescence emissions by e-beam and e-beam stabilized discharge excitation of a high density supersonic gas flow at very low temperature, and this, with a quite high intrinsic efficiency.

Moreover experiments at I.M.F.M. have also shown that supersonic flow may be very helpful to control and reduce acoustic disturbances following high energy absorption by the medium. This research will be extended in laser kinetics and gas dynamics as well as in high repetition rate, excitation systems studies, in the frame of development of high average power high efficiency flowing electron transition lasers.

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