JP0150860

JAERI-Conf 2001-011

35. Krypton Excimer Laser Oscillation by Discharge Pumping

Takahiro SHIRAI, Yoshitaka TABE, Shoichi KUBODERA Wataru SASAKI,
Department of Electrical and Electronic Engineering and Photon Science Center, Miyazaki University,
1-1 Gakuen Kibanadai Nishi, Miyazaki, Miyazaki 889-2192 Japan
Junji KAWANAKA
Advanced Photon Research Center, Kansai Research Establishment,
Japan Atomic Energy Research Institute
8-1 Umemidai Kizu-cho, Souraku-gun, Kyoto 619-0215 Japan
Tatsushi IGARASHI
Gigaphoton Inc., 400 Yokokurashinden, Oyama, Tochigi 323-8558 Japan

We have demonstrated vacuum ultraviolet (VUV) laser oscillation of the krypton excimer (Kr_2^*) excited by a compact self-sustained discharge device. We have observed a spectral narrowing of the Kr_2^* emission centered at 147.8 nm. A deconvoluted spectral width is 0.5 nm (FWHM), which reveals a contrast to a 13 nm spectral width of the spontaneous emission. The Kr_2^* intensity has increased one order of magnitude when a charging voltage was increased larger than 29 kV. The success of the lasing in the VUV spectral region has been attributed to the success of a stable glow discharge of Kr at 10 atm. The pulse width of the VUV laser radiation is 400 ns (FWHM). The maximum output energy measured is as large as 150 μJ.

Keywords: Vacuum Ultraviolet, Krypton Excimer, Excimer Laser, Discharge

1. Introduction

Rare gas excimers are one of the few emission sources in the vacuum ultraviolet (VUV) spectral region. Center wavelengths of rare gas excimer emissions are 126 nm, 147 nm, and 172 nm for Ar_2^*, Kr_2^*, and Xe_2^*, respectively. This corresponds to high photon energy between 7 and 10 eV. Short wavelength lasers are advantageous for various application fields, such as VUV optical lithography. On the other hand, high-energy photons will induce bond breaking of molecules, leading to a novel optical CVD technique [1]. The rare gas excimer lasers have been realized only by e-beam pumping [2,3]. The e-beam device is rather large and may not be appropriate for repetitive operation. Self-sustained discharge pumping may thus be an alternative way to realize compact rare gas excimer lasers in repetitive operation. There are considerable efforts to demonstrate discharge pumped rare gas excimer lasers [4]. No successful laser oscillation, however, has been reported until now, mainly because of the difficulty of obtaining a stable glow discharge in high-pressure rare gases. As a result of solving this difficulty, we have demonstrated VUV laser oscillation of the Kr_2^* excited by a compact discharge device [5]. We have observed a considerable spectral narrowing of the Kr_2^* emission centered at 147.8 nm. The spectral width decreased from 4.0 nm to 0.5 nm (FWHM) when a charging voltage was increased from 27 kV to 31 kV. The pulse width of the 147.8 nm laser was 400 ns (FWHM) and the maximum optical energy measured was as large as 150 μJ [6].

2. Experiment

Fig. 1 shows the schematic diagram of the experimental apparatus. The laser tube was originally designed and constructed for the F_2 and rare gas halide lasers [7]. The discharge tube contained a pair of electrodes. The distance of the electrodes was optimized at 5 mm. The widths of the cathode and anode were 3 cm and 5 cm, respectively. The electrode shape was thus asymmetric. The length of the electrodes was 110 cm. Fifty-one preionization pins in two parallel rows were placed near the cathode inside the tube. A pair of dielectric coated mirrors consisted of an optical cavity. A reflector had a reflectivity of 85% at 148 nm. An output coupler possessed the reflectivity of 85% with 6% transmission at 148 nm. The distance between the two mirrors was 135 cm. High pressure Kr inside the laser tube was sealed with two MgF_2 windows.

The discharge circuit was a charge transfer type with automatic UV preionization. The stored charges in the primary capacitor (150 nF) were transferred into the 127 nF secondary capacitors placed inside the laser tube through 102 UV preionization pins. The ratio of the primary and secondary capacitance was optimized. The inductance of 10 nH in a main discharge loop was evaluated from a time-resolved voltage signal, leading to The static discharge impedance less than 1 Ω. The inductance of 1.7 μH was introduced in the primary discharge loop to ensure a good electrical contact between a high voltage feed-through and preionization pins inside. This inductance also regulated the timing between the switching and the gas breakdown. A mid-plane configuration was used as a gap switch. The discharge was operated at a single shot base.

The emission from the discharge region was detected with a solar blind VUV photomultiplier coupled to a 20 cm VUV spectrometer. The slit widths of the spectrometer were kept as narrow as possible to avoid any damage of optics caused by the intense VUV emission, resulting in the spectral resolution of the system to be 0.4 nm (FWHM). Time-resolved signals of the VUV emissions were recorded using a 2 GHz digital oscilloscope. All electronic devices were connected to a personal computer for data acquisition, storage and further data processing. In order to minimize the impurities inside the laser tube, a turbo molecular pump in addition to a rotary pump was used to evacuate the laser tube as low as 10^{-6} Torr. A laboratory-grade Kr (99.999%) was used throughout the experiments.

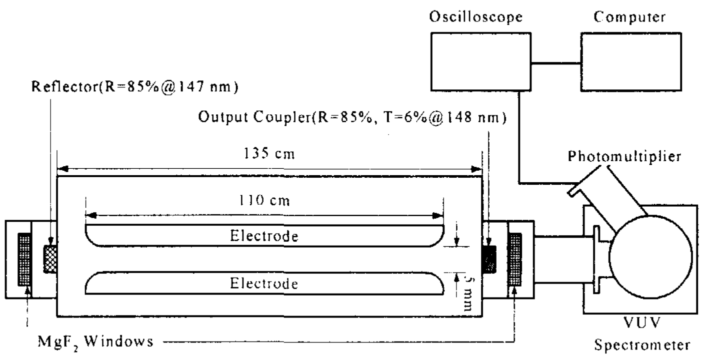

Fig. 1 The schematic diagram of the experimental apparatus

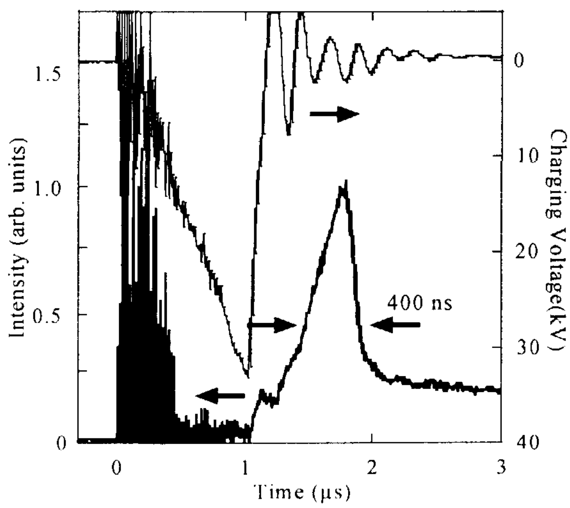

Fig. 2 Time-resolved voltage signal and time-resolved Kr_2* emission waveform

3. Experimental results

Fig. 2 shows a time-resolved voltage signal, together with a time-resolved Kr_2* emission waveform. The spike at the time zero was caused by a switching noise. After the gas breakdown at 1.1 μs, the voltage signal started ringing with duration of 200 ns (FWHM), when the electrical power was deposited inside the discharge. The VUV emission evolved at the time of the breakdown and reached at the peak in 400 ns. The half width of the Kr_2* emission was 400 ns. This temporal behavior was much narrower than those observed at lower power deposition. Note that no noise caused by arcing is shown in the afterglow regime. The stored energy in the primary capacitor was calculated to be 70 J. When 80% of the energy was transferred inside the discharge, the estimated deposited energy was approximately 10 Jcm^{-3}. We evaluated the discharge volume by inspecting the width of scars left on the electrodes. Although the measurement of the discharge current was not performed, the deposited power of more than 20 $MWcm^{-3}$ was estimated if assuming the current signal having a similar ringing behavior to that of the voltage signal.

The charging voltage dependence of the Kr_2* emission intensity is shown in Fig. 3. Stable self-sustained discharge was obtained even at 10 atm of Kr at different charging voltages between 27 and 31 kV, which was verified from the time-resolved voltage waveforms. When the voltage exceeded 29 kV, the Kr_2* emission intensity abruptly increased. The peak intensity at 31 kV became almost one order of magnitude as high as that at 29 kV. The time-resolved signals also changed dramatically. At the voltage of 29 kV, the time-resolved signal had a 2.6 μs width (FWHM) with a rise time of 1.2 μs. On the other hand, the time-resolved waveform showed a width of 400 ns (FWHM) with a rise time of 400 ns at the voltage of 31 kV. The difference of the intensity and pulse shape represents the voltage threshold behavior of the VUV emission and indicates the onset of the lasing.

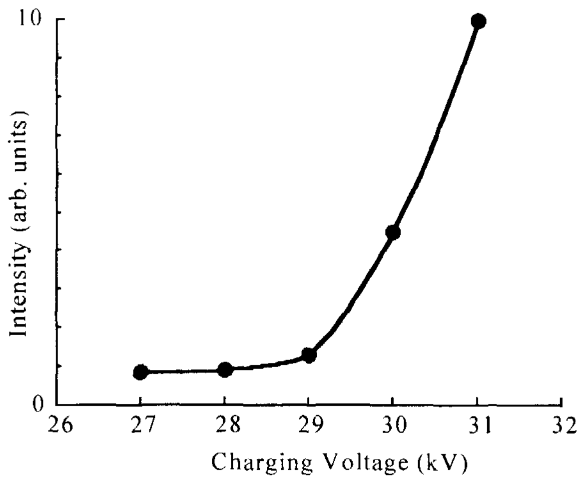

Fig. 3 The charging voltage dependence of the Kr_2* peak intensity

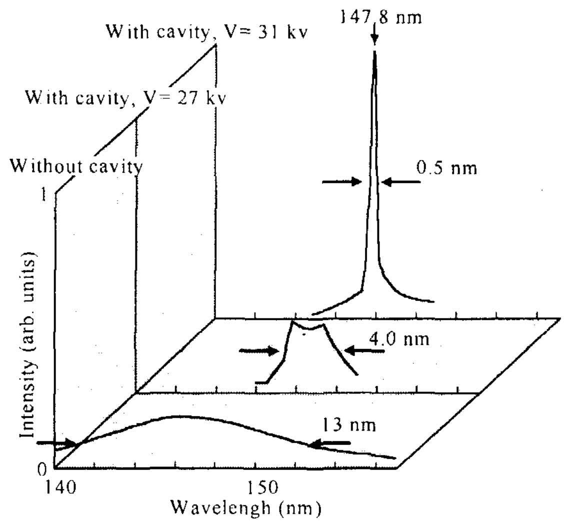

Fig. 4 Observed spectral narrowing at different voltages

In order to confirm this threshold behavior, the emission spectra were measured at different voltages. The result is shown in Fig. 4. At the voltage of 27 kV, the spectral width was 4.0 nm (FWHM). On the other hand, a considerable spectral narrowing of 0.4 nm (FWHM) was observed when the charging voltage was increased to 31 kV. A deconvoluted spectral width was evaluated to be 0.5 nm (FWHM) by taking into account of the transmission function of the detection system. Note that the spectral width of the spontaneous emission of the Kr_2 radiation was measured to be 13 nm (FWHM). This spectral narrowing is the direct evidence of the Kr_2 laser oscillation at 148 nm. An output laser energy was measured by using a calorimeter (Gentec ED-100A). The maximum output energy measured was as large as 150 μJ. Note that this calorimeter has not been calibrated at the laser wavelength, therefore, this energy value is somewhat underestimated.

4. Conclusions

We have demonstrated laser oscillation of Kr_2* by self-sustained discharge excitation for the first time to our knowledge. The narrowed spectral width was 0.5 nm (FWHM). The maximum output energy at 148 nm was as large as 150 μJ. The demonstration of the VUV laser oscillation is mainly attributed to the success of the self-sustained glow discharge of high pressure Kr. The discharge pumped VUV Kr_2* excimer laser would open up various application fields where such a short wavelength laser has been much required.

References

[1] A. Yokotani, N. Takezoe, K. Kurosawa and W. Sasaki, Nonlinear Opt. 22, 465 (1999).
[2] H. A. Koeehler, L. J. Ferderber, D. L. Rehhead and P. J. Ebert, Appl. Phys. Lett. 21, 198 (1972).
[3] Y. Uehara, W. Sasaki, S. Saito, E. Fujiwara, Y. Kato, M. Yamanaka, K. Tsuchida, and J. Fujita, Opt. Lett. 9, 539 (1984).
[4] T. Sakurai, N. Goto, and C. E. Webb, J. Phys. D 20, 709 (1987).
[5] T. Shirai, W. Sasaki, S. Kubodera, J. Kawanaka, and T. Igarashi, Proc. SPIE (in press, 2001).
[6] W. Sasaki, T. Shirai, S. Kubodera, J. Kawanaka, and T. Igarashi (in preparation).
[7] K. Yamada, K. Miyazaki, T. Hasama, and T. Sato, Appl. Phys. Lett. 54, 597 (1989).