

Simultaneous Multiwavelength Operation of a Commercial Rare Gas Halide Laser

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Abstract—Simultaneous dual wavelength operation of a commercial-discharge excited rare gas halide excimer laser is reported for the first time. A combined energy output in excess of 20 mJ was obtained for the 193 and 248 nm ArF and KrF $B \rightarrow X$ transitions oscillating simultaneously, and also for the 248 and 351 nm KrF and XeF transitions. Analysis indicates that significantly higher dual wavelength energies should be possible.

INTRODUCTION

FOR applications in areas such as spectroscopy, optical diagnostics, materials processing, and medicine, it may be useful to have the capability of operating a single rare gas halide excimer laser system at two or more wavelengths. In this letter, we report the first demonstration of relatively efficient, simultaneous oscillation of two UV rare gas halide transitions in a commercial excimer laser.

In a previous investigation, it was shown that an electron-beam excited medium that had been optimized for efficient blue/green XeF($C \rightarrow A$) laser oscillation also exhibited strong net gain on the UV $B \rightarrow X$ transition, and that simultaneous laser oscillation on both transitions was possible [1]. Subsequently, relatively efficient (~ 0.25 percent), simultaneous UV/visible XeF laser oscillation was achieved through use of an optimized dual wavelength resonator along with addition of Kr to the gas mixture [2], [3]. In that work, the intensity of the 248 nm KrF($B \rightarrow X$) fluorescence was observed to be comparable to that of the 351 nm XeF($B \rightarrow X$) fluorescence under conditions for which the dual XeF $B \rightarrow X$ and $C \rightarrow A$ laser output energies were equal. Since the kinetics of the $B \rightarrow X$ transitions of KrF and XeF are actually less competitive than those of the XeF $B \rightarrow X$ and $C \rightarrow A$ transitions, this observation suggested that efficient, simultaneous multiple wavelength oscillation on $B \rightarrow X$ rare gas halide transitions should be possible using appropriate gas mixtures in a commercial-discharge excited excimer laser.

EXPERIMENTAL APPARATUS AND PROCEDURE

In order to investigate the possibility of simultaneous "dual wavelength" operation, we used an unmodified commercial excimer laser. This laser has a discharge

length of 50 cm, an interelectrode spacing of 2.6 cm, and an active discharge volume of approximately 0.12 l. The optical resonator consists of a MgF₂ coated aluminum high-reflectivity mirror and a CaF₂ window that serves as the output coupler. The distance between the window and the mirror is 75 cm. The laser was operated with a discharge voltage of 30 kV and a repetition frequency in the 3–10 s⁻¹ range. Laser gases were mixed inside the laser cavity which had been thoroughly passivated through several months' use with mixtures containing only fluorides. Gas pressures were measured with the built-in manometer of the laser. In order to obtain accurate gas pressure measurement when mixture constituents with partial pressure below 50 mbar were required, the low partial pressure gases were prediluted in helium, the recommended buffer gas for rare gas fluoride laser operation. For each change in gas mixture, a new fill was used.

The total output energy of the laser was measured by means of two calibrated Gentec pyroelectric energy meters (Models ED 200 and ED 500). A quartz flat served as a beam splitter to guide part of the laser output to a vacuum photodiode. Interference and color glass filters were used for spectral selection of the laser transitions. Quartz neutral-density filters served as attenuators for the laser beam. This arrangement permitted an accurate determination of the total laser energy without regard to wavelength, as well as independent laser energy and temporal pulse shape measurements for each UV laser transition.

The total energy output of our laser operating on each of the rare gas fluoride $B \rightarrow X$ transitions individually was (90 \pm 20) mJ for ArF (193 nm), (250 \pm 40) mJ for KrF (248 nm), and (80 \pm 20) mJ for XeF (351 nm). These values were obtained using the optimum three-component gas mixtures recommended by the manufacturer. The maximum energy values for KrF and XeF are in accord with the manufacturer's specifications, whereas the measured ArF output is approximately half of the optimum energy output for this laser. The 193 nm ArF laser transition is by far the most sensitive of the rare gas fluorides to gradual deterioration of system components through normal use [4]. Therefore, considering the age and prior history of the laser used in this investigation, the reduced ArF laser energy level is not unusual.

RESULTS AND ANALYSIS

In order to obtain dual wavelength oscillation on the KrF and XeF transitions, xenon was added gradually to the

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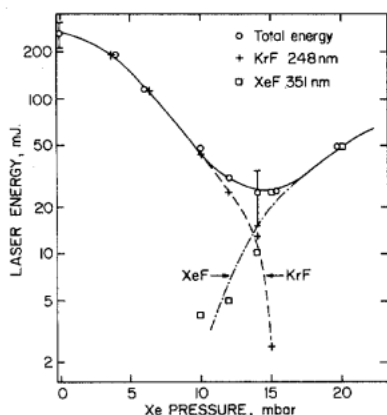


Fig. 1. Total UV laser energy and KrF and XeF laser energies as a function of Xe pressure for a mixture comprised of 6 mbar F_2 , 150 mbar Kr and He at an initial total pressure of 2.5 bar. In the absence of Xe, this mixture is optimized for KrF laser oscillation alone. The discharge voltage was 30 kV.

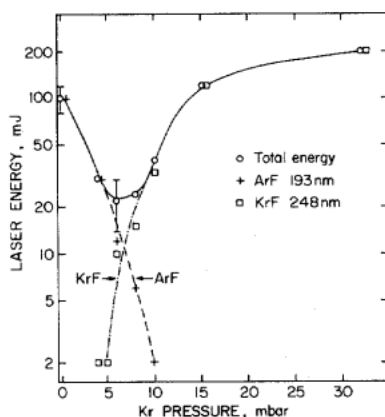


Fig. 2. Total UV laser energy and ArF and KrF laser energies as a function of Kr pressure for a mixture comprised of 7.5 mbar F_2 , 350 mbar Ar and He at an initial total pressure of 2.2 bar. In the absence of Kr, this mixture is optimized for ArF laser oscillation alone. The discharge voltage was 30 kV.

three-component He-Kr- F_2 mixture that had been optimized for 248 nm KrF laser oscillation alone. A similar experiment was carried out starting with a mixture optimized for 193 nm ArF oscillation; in this case, Kr was added gradually to the optimum He-Ar- F_2 mixture. The results of these experiments are shown in Figs. 1 and 2.

As xenon is added to the mixture optimized for KrF laser oscillation, the total laser output energy decreases to a value about one tenth the initial value typical of KrF alone. A minimum is established for a xenon pressure of about 14 mbar, above which the total energy increases (Fig. 1). The spectrally resolved data show that initially the KrF laser energy decreases with increasing xenon pressure. For xenon pressures between 10 and 15 mbar, both the 248 nm KrF and the 351 nm XeF lasers exhibit laser action simultaneously. At a xenon pressure of ~14 mbar, the energy of each laser is 10–15 mJ, resulting in a total combined energy of about (25 ± 10) mJ, corresponding to an overall efficiency of ~0.2 percent based on the energy stored in the capacitors. For xenon pressures above 15 mbar, the laser operates only on the 351 nm XeF tran-

sition, achieving an output energy at 20 mbar that approaches the maximum value that can be obtained using the optimized three-component XeF laser mixture. Since no effort was made to optimize the fractional concentrations of Kr, Xe, or F_2 in the four-component mixture of Fig. 1, it seems likely that higher dual laser energy could be achieved with mixture reoptimization and/or that the output from a four-component mixture optimized for XeF oscillation alone might actually be higher than that obtainable using the recommended three-component mixture.

Dual KrF and XeF laser oscillation was also demonstrated [5] using another laser of the same type that previously had been operated for several months using an XeCl gas fill. The dependence of the total laser energy on Xe pressure was found to be essentially the same as that shown in Fig. 1, but not until the system had been operated with rare gas fluoride mixtures for nearly a week. Thus, the relatively lengthy fluorine passivation procedure that is typical of conversion from chloride to fluoride operation for lasers of this general type is exceptionally important for the reduced laser energy levels characteristic of dual UV wavelength operation.

Behavior generally similar to that of Fig. 1 was also observed for the dual ArF and KrF laser experiments (Fig. 2). Starting with a mixture optimized for ArF laser oscillation alone, upon addition of Kr, the total laser energy decreases from its initial level characteristic of ArF (but below specification as described previously). In this case, the minimum in total laser energy is reached at a Kr pressure of ~7 mbar. At this point, the combined ArF and XeF laser energies are equal and the total output of ~25 mJ is almost exactly the same as that of the KrF and XeF lasers, even though the initial ArF laser energy was much lower than that of the KrF laser (Fig. 1). For Kr pressures higher than 7 mbar, the KrF laser takes over, reaching an energy level at 30 torr for this nonoptimized four-component mixture that, at ~200 mJ, is practically equivalent to that typical of the optimized three-component KrF mixture, once again suggesting that an optimized four-component mixture might yield a higher KrF laser energy than a three-component mixture.

Attempts to demonstrate simultaneous ArF and XeF oscillation were not successful. Addition of even small amounts of Xe (~1 mbar) to the optimized ArF mixture resulted in a sharp decrease from the already subspecification initial level for ArF alone. However, further increases in Xe pressure did result in XeF laser oscillation.

For the conditions in Figs. 1 and 2, the laser pulsewidth decreased gradually as the third rare gas was added to produce dual UV laser action. When xenon was added to the optimized three-component KrF mixture, the KrF pulsewidth decreased from 20 ns to about 9 ns at the total energy minimum occurring for a Xe pressure of ~14 mbar (Fig 1). For this xenon pressure, the XeF laser pulsewidth was about 8 ns and increased gradually to about 15 ns with increasing xenon pressure. Thus, the relative decrease in the total laser peak power accompanying dual laser operation is only about half the relative decrease in the total

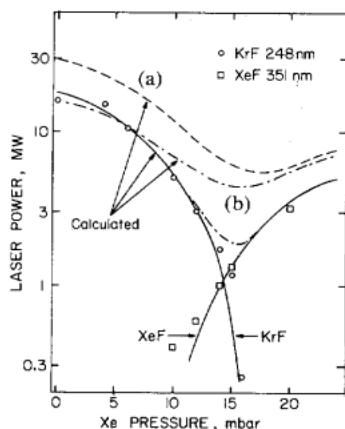


Fig. 3. KrF and XeF laser power corresponding to the conditions of Fig. 1. The solid lines are the result of calculations based on the medium/resonator properties typical of the laser used in this investigation following the procedure described in the text. The possible effects of increasing the length of the active medium by 50 percent (a) or of replacing the CaF_2 output window with a mirror having a reflectivity of 20 percent (b) are also shown.

laser energy. The peak powers for the KrF and the XeF dual laser corresponding to the condition of Fig. 1 are shown in Fig. 3. For the conditions of combined laser action, the pulses from both lasers overlapped temporarily.

In order to evaluate the prospects for improved dual wavelength laser performance, we have developed an approximate analysis relating KrF and XeF laser gain in a rare gas fluoride medium containing both Kr and Xe. When combined with Schindler's theory [6] of optical power extraction, modified to account for laser oscillation at two wavelengths, this approach permits us to relate laser power to experimental resonator variables such as length and output coupling, and to KrF/XeF medium properties such as saturation intensity, small-signal gain, and absorption loss. The total pumping density was distributed between production of KrF and XeF by defining the fractional pumping power density contributing to XeF formation as δ_x . Within the framework of our analysis, it is easily shown that the KrF small-signal gain coefficients are then related in the following way:

$$g_{\text{XeF}} = g_{\text{XeF}_0} \delta_x$$

$$g_{\text{KrF}} = g_{\text{KrF}_0} (1 - \delta_x)$$

where g_{XeF_0} and g_{KrF_0} are the gain coefficient for either a XeF or KrF laser alone. Assuming that the primary transfer reactions from the KrF chain to the XeF chain are linear in Xe pressure, the variable δ_x is then simply proportional to Xe pressure.

For the present purposes, medium properties typical of discharge-excited KrF and XeF lasers similar to ours were used in the analysis [7], [8]. Fig. 3 presents measured and computed values of dual KrF and XeF laser power corresponding to the conditions of Fig. 1. Using the resonator parameters of our laser and guided by the experimental data reported by Gower and co-workers [7], [8], values of KrF medium properties were selected so as to ensure agreement between measured and computed KrF laser

power with no Xe in the mixture, i.e., the left boundary of Fig. 3. Using those specific values of KrF gain, absorption, and saturation intensity, a complementary set of XeF medium properties was chosen [9]. The constant of proportionality relating the fractional XeF power density δ_x to Xe pressure was then selected so as to ensure agreement between measured and computed dual laser power for the Xe pressure at which the KrF and XeF laser power are equal, i.e., a Xe pressure of 14 mbar. With this information, the laser power for KrF and XeF could be determined for all Xe pressures over the range of interest. The solid lines in Fig. 3 clearly show that the self-consistent set of KrF and XeF variables so determined is capable of reproducing the qualitative and quantitative variation of dual laser power that we have observed.

Using the set of variables resulting in the solid lines shown in Fig. 3, the calculation was then repeated for a discharge length 50 percent larger than that of the laser used in this investigation [Fig. 3(a)]. At the end points (Xe pressure 0 or ~25 mbar), the respective KrF and XeF laser powers increase by approximately 50 percent, as should be the case since the laser medium is nearly saturated with either KrF or XeF operating alone. However, for Xe pressures typical of the minimum dual laser power for which the medium is far from saturation, a 50 percent increase in discharge length results in a factor of three increase in laser power. Fig. 3(b) illustrates the effect of replacing the CaF_2 output window ($R < 10$ percent) with a mirror having a 20 percent reflectivity at both laser wavelengths. In this case, the minimum dual laser output is increased by more than a factor of two. These illustrative results suggest that dual laser powers substantially in excess of those demonstrated in this investigation should be attainable.

SUMMARY

We have demonstrated that an unmodified commercial excimer laser is capable of simultaneously producing relatively high-energy laser oscillation on two different UV rare gas halide transitions by way of an appropriate choice of mixture composition. Furthermore, analysis indicates that with relatively minor changes in discharge and/or resonator properties, dual wavelength laser energy/efficiency levels comparable to those typical of a single wavelength rare gas halide laser should be possible.

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- [9] The parameters used in the illustrative examples of Fig. 3 were, for KrF and XeF, respectively, saturation intensity $2.5 \text{ MW} \cdot \text{cm}^{-2}$ and $1.1 \text{ MW} \cdot \text{cm}^{-2}$, small-signal gain coefficient $8 \text{ percent} \cdot \text{cm}^{-1}$ and $5.5 \text{ percent} \cdot \text{cm}^{-1}$, and unsaturated absorption coefficient $0.6 \text{ percent} \cdot \text{cm}^{-1}$ for both. The reflectance of the high-reflectivity mirror was taken as 80 percent for both wavelengths. Although these variables do not constitute a unique set, they do represent a physically reasonable, self-consistent set that, within the framework of our illustrative analysis, is capable of reproducing the observed experimental dual wavelength output. For this reason, the curves of Fig. 3 illustrating the effect of changes in discharge length and/or output window are felt to provide a reasonable first-order estimate of the potential for improving dual laser performance.