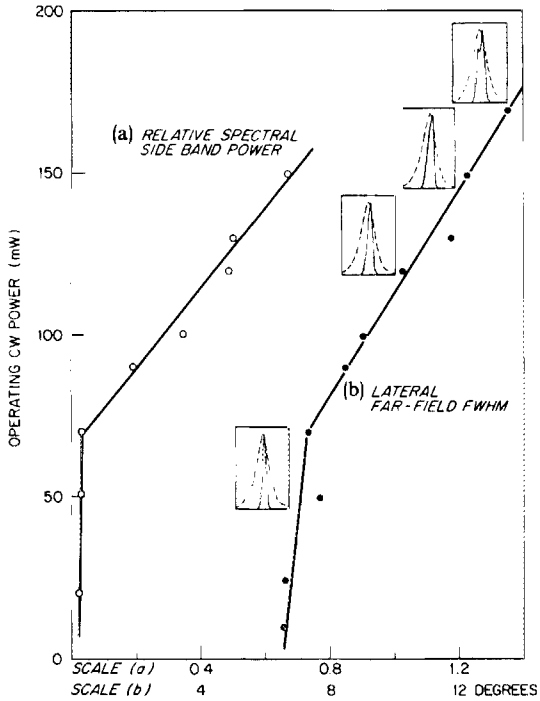

FIG. 3. Ratio of total spectral side band power to main line power, curve (a), and FWHM of the parallel far-field pattern, curve (b), plotted as a function of operating power level. Note similarities. Inserts show the development of asymmetry in the far-field patterns.

far-field patterns but higher order spectral modes as well.

Several diode lasers of the type described above are in the process of being life tested. Preliminary results indicate that ongoing operation at 20 mW cw at 30 °C is stable to (at least) 4000–5000 h, but at 100 mW cw at 30 °C the lifetime was limited to 700 h. While we can as yet offer no discussion of failure mechanism, it is worth noting that no clear visual signs of catastrophic facet damage are commonly observed.

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Efficient narrow spectral output in the blue-green region from an injection-controlled electron-beam excited XeF ($C \rightarrow A$) laser

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Efficient, narrow spectral output has been achieved by injection control of an electron-beam excited XeF ($C \rightarrow A$) laser medium using a 482-nm dye laser pulse having a spectral width of 0.01 nm. The energy density and intrinsic efficiency characteristic of the amplified output beam were 3 J/l and approximately 2.5%, respectively, and the spectral width was on the order of that of the injected pulse.

In recent years narrow bandwidth ($\lesssim 0.01$ nm), tunable laser operation has been demonstrated by injection locking electrically excited rare gas-halide lasers such as KrF (248 nm)[1] and XeF (351 nm),[1,2] and HgBr (502 nm).[3] Additionally, the UV output of lasers such as XeCl (308 nm) has been Raman converted to several specific wavelengths in the visible region, also with narrow spectral width.[4] Although the high efficiency ($\geqslant 1\%$) typical of these lasers operating as free-running oscillators was preserved in the narrow wavelength-tuned output, their tuning *range* is limited to about 1

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nm. In contrast, the very broadband XeF ($C \rightarrow A$) laser, centered in the blue-green region at 485 nm, has been tuned continuously from about 450 to 510 nm with a spectral width on the order of a few nanometers, using either intracavity optical elements[5,6] or dye laser pulse injection.[7] However, in these experiments both the free-running and tuned laser output were extremely inefficient ($\ll 1\%$).

Recently, very significant improvement in the performance of an electron-beam (e-beam) excited XeF ($C \rightarrow A$) laser has been achieved by selective tailoring of the gas mixture so as to minimize transient absorption.[8–10] Use of multicomponent gas mixtures comprised either of Ar-Xe-F_2-NF_3 (Refs. 8 and 9) or of Ar-Kr-Xe-F_2-NF_3 (Ref. 10) has resulted in laser pulse energy density values in the 1.5–3.0 J/l range with an intrinsic efficiency of approximately 1.5%, a performance level which, for the first time, is comparable to that typical of the $B \rightarrow X$ rare gas-halide and mercury-halide lasers. In these studies the free-running XeF ($C \rightarrow A$) laser output was centered at 480 nm with a bandwidth of ~ 25 nm (FWHM). However, measurements[9,10] showed that the gain extended over a much larger spectral range and exhibited a relatively weak dependence on wavelength. These results indicate that it should be possible to tune the XeF ($C \rightarrow A$) laser continuously throughout the entire blue-green region, with narrow spectral width and with an efficiency typical of that demonstrated in the free-running mode. In this letter we report efficient (~ 2.0–3.0%), narrow spectral output ($\Delta\lambda \sim 0.01$ nm) from an XeF ($C \rightarrow A$) laser medium by amplification of an injected dye laser pulse.

Transverse laser excitation was provided by an e-beam with an electron energy of 1 MeV and a pulse duration of 10 ns (FWHM). The e-beam current density at the center of the optical axis was ~ 200 A cm^{-2}, as measured with a Faraday probe. Specific details of the experimental arrangement and related diagnostic apparatus are described in Ref. 9. For the present purposes the gas mixture was composed of 6.5 atm Ar, 16 Torr Xe, 8 Torr F_2, and 8 Torr NF_3. Good mixing of the component gases and thorough fluorine passivation of the stainless steel reaction cell were found to be absolutely essential in order to ensure reliable laser performance. The source of the injected radiation was a narrow bandwidth excimer-pumped dye laser system (Lambda-Physik models EMG 100 and FL 2002). This reference oscillator arrangement delivered up to 12 mJ in a 10 ns pulse, tunable from 440 to 540 nm using Coumarin dyes 47, 102, and 307. The spectral width of the seed pulse was 0.01 nm as measured with a monitoring étalon.

The collimated dye laser pulse was injected through a small hole (2 mm diameter) in the concave back mirror of an intracell positive branch confocal unstable resonator[1] as illustrated in Fig. 1. Two different resonators were used having radii of curvature for the concave mirrors of either 1.5 or 2.0 m, and for the corresponding smaller convex mirrors of either 1.22 or 1.75 m; the mirror separation was about 13.0 cm, depending on the specific resonator. The concave mirrors were covered with a broadband coating that was totally reflective from 440 to 530 nm, while the coating on the convex output reflector (a meniscus lens) was limited to a diameter of 1.4 cm. The thin outer annular region of the output

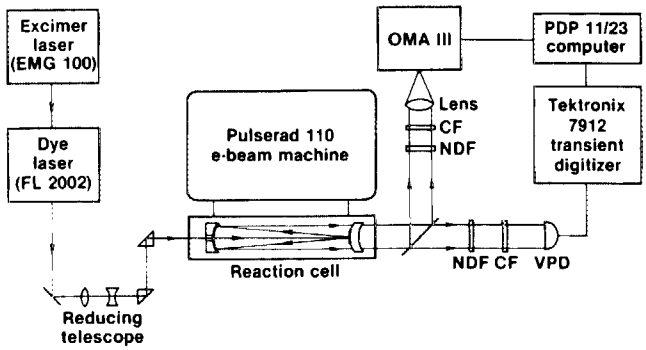

FIG. 1. Schematic illustration of experimental arrangement. NDF = neutral density filter, CF = color-glass filter, VPD = vacuum photodiode.

mirrors was AR coated on both sides. These elements resulted in cavity magnification (M) values of 1.23 and 1.14, corresponding to output coupling of 34 and 24%, respectively, values that are very much higher than the $\sim 5\%$ previously found to be optimum for a free-running stable resonator.[9,10] Since oscillation in this type of unstable resonator builds up most readily in the "lossless" paraxial region,[1] and since (for these small magnifications) the injection hole constitutes a large loss ($\sim 70\%$) to the paraxial volume, significant self-oscillation (injected or not) is not possible. Indeed, the output energy obtained by operating these resonators as free-running oscillators was three to four orders of magnitude lower than that obtained using an optimized stable resonator under otherwise similar conditions.[10] Thus, in this case the primary role of the cavity is to serve as the beam-expanding telescope of a regenerative amplifier. Hence the term *injection controlled* is used instead of injection locked.

The temporal relationships among the injected 482-nm dye laser pulse, the e-beam excitation pulse, the XeF ($C \rightarrow A$) laser output at 482 nm, and the free-running broadband XeF ($C \rightarrow A$) laser output are shown in Fig. 2. Also shown for

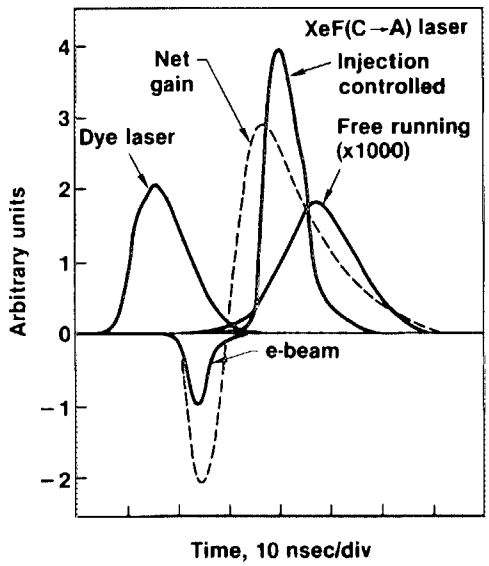

FIG. 2. Approximate temporal relationships among the 482-nm injected dye laser pulse at the cavity input hole, the e-beam excitation pulse, the 482-nm XeF ($C \rightarrow A$) laser output at the cavity exit, and the broadband free-running XeF ($C \rightarrow A$) laser output. Also shown is the typical temporal evolution of the zero field net gain at 488 nm. For the present mixture, 6.5 atm Ar, 16 Torr Xe, 8 Torr NF_3, and 8 Torr F_2, the peak gain is $\sim 2.75\%$ cm^{-1} (Ref. 10).

illustrative purposes is the temporal evolution of the *net* gain at 488 nm. The causes of the strong initial absorption occurring during the *e*-beam excitation pulse have been identified and are explained in detail elsewhere.[9,10] Because of the low magnification, it takes ~10 round trips through the ~13-cm-long cavity before the injected dye laser pulse expands to fill the active cavity volume, requiring a time of ~10 ns. Thus, the duration of the injected pulse, the rise time and the duration of the gain, and the cavity fill time are all about the same. For this reason, the timing of the dye laser pulse with respect to the firing of the *e*-beam was found to be quite critical and had to be controlled to within a few nanoseconds in order to obtain repeatable results.

Figure 3 shows the dependence of the XeF ($C \rightarrow A$) output pulse energy on the energy of the injected dye laser pulse for the $M = 1.23$ cavity. Because of the low magnification, in the *absence* of *e*-beam excitation 60 to 70% of the dye laser energy is reflected back out through the 2-mm-diam hole in the concave mirror. The fraction of the input pulse that escapes through the hole when the *e*-beam *is* fired is likely to be somewhat lower due to spatial nonuniformity of the gain medium. Thus, the input energy shown in Fig. 3 represents an upper limit to the actual intracavity value, and the output-input ratio that can be inferred from the data is therefore a lower limit. The linear dependence of the output pulse energy on dye laser input energy for a three order of magnitude variation of the latter indicates that the cavity/medium combination is acting as a multipass amplifier for the present conditions and that the gain is not significantly saturated until high input energies are reached. Such behavior is consistent with the very low output obtained with the resonator operating as a free-running oscillator. However, saturation of the gain medium appears to occur for input pulse energies above approximately 0.1 mJ. The 20-mJ maximum output for the $M = 1.23$ cavity corresponds to an energy density of 1 J/l and an intrinsic energy utilization efficiency of approximately 1%, based on an active volume of 20 cm^3 and an *e*-beam energy deposition of ~100 J/l.[9] For the same conditions the $M = 1.14$ cavity resulted in an output energy an order of magnitude higher than the $M = 1.23$ cavity when the input energy was $\leqslant 0.01$ mJ, with a maximum output of over 60 mJ at saturation, corresponding to energy density and intrinsic efficiency values of 3 J/l and approximately 2.5%, respectively.[11] For the net gain typical of these conditions (Fig. 2) the significantly increased output obtained using the $M = 1.14$ cavity compared to that of the $M = 1.23$ cavity is consistent with the ~50% longer amplification path length of the former.

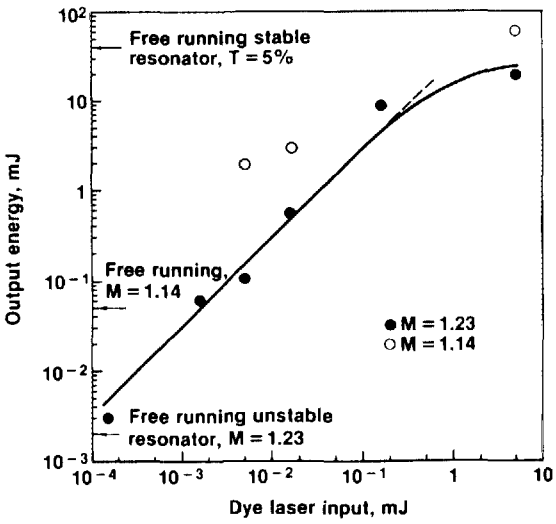

FIG. 3. XeF ($C \rightarrow A$) output pulse energy dependence on the injected dye laser energy, both at 482 nm, measured using a calibrated vacuum photodiode detector. The gas mixture was comprised of 6.5 atm Ar, 16 Torr Xe, 8 Torr NF_3, and 8 Torr F_2; and volumetric *e*-beam energy deposition was ~100 J/l (Ref. 9). Laser output levels obtained with unstable and stable (optimized) free-running oscillators are indicated.

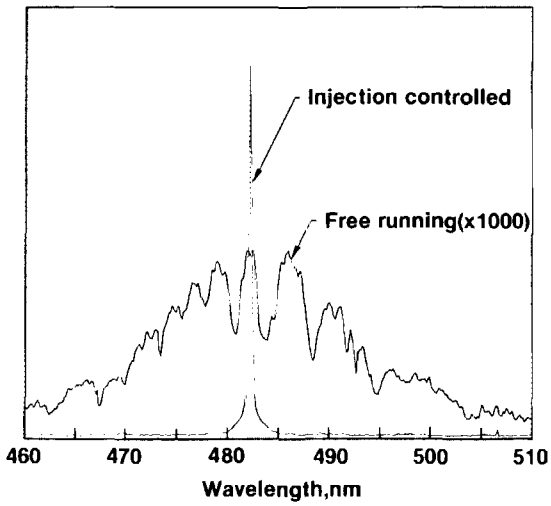

FIG. 4. XeF ($C \rightarrow A$) spectra for the free-running and injection-controlled conditons of Fig. 3. The resolution limit of the measurement system was 0.5 nm.

Presented in Fig. 4 is the broadband XeF ($C \rightarrow A$) spectrum typical of the unstable (or stable[9,10]) resonators operating as free-running oscillators, compared with that of the injection-controlled XeF ($C \rightarrow A$) amplifier. The indicated ~0.5-nm width of the amplified 482-nm pulse reflects the resolution limit of our present measurement system. Preliminary evaluation of the spectral characteristics of the narrowed XeF ($C \rightarrow A$) output indicates that the spectral width is nearly the same as that of the dye laser input, i.e., $\Delta\lambda \sim 0.01$ nm. In these experiments the dye laser output was tuned so as to coincide with a maximum in the free-running laser spectrum (Fig. 4). However, tuning the input a few nanometers to the location of an absorption valley resulted in no significant changes in the output. Although the broadband laser spectrum of a free-running oscillator (stable or unstable) typically is limited to the 465–495-nm range within which the gain is a maximum, measurements show[9,10] that the net gain is reduced from its maximum at ~485 nm by only ~20% for wavelengths as low as 460 nm and as high as 510 nm, indicating that continuous tuning over a broad range with high-energy output should be possible.

This investigation has shown that simultaneous narrow spectral output and efficient energy extraction can be obtained using an XeF ($C \rightarrow A$) laser medium to amplify an injected dye laser pulse. These results indicate that *efficient*, narrow spectral output should be attainable throughout the entire blue-green region using an injection-controlled, elec-

trically excited XeF ($C \rightarrow A$) medium, with the medium serving either as an amplifier as in the present investigation or as an injection-locked oscillator. However, longer gain lengths will be required for true efficient oscillator operation of an unstable cavity.

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[11]In the work reported herein only Ar-Xe-NF_3-F_2 mixtures were used. Five component mixtures containing Kr require nearly an order of magnitude less F_2 for optimum performance, a factor which complicates the passivation procedure for the present apparatus. Nonetheless, the magnitude of the net gain is significantly larger and its duration longer for Kr-containing mixtures than is the case for the mixture used in the present work (Ref. 10). This indicates that much higher levels of output energy/efficiency should be attainable with no increase in either the energy of the injected input pulse or the *e*-beam excitation pulse.

Energy partitioning between the equilibrated *A* and *X* states of the CN radical formed in the C + N_2O reaction

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Similar populations have been observed between the *A* and *X* states of the CN radical, formed in the C + N_2O chemical reaction. Relative vibrational populations were measured by laser-induced fluorescence (*X* state) and chemiluminescence (*A* state). The electronic branching ratio was then obtained by assuming a Boltzmann equilibrium between the $v'' = 4$–6 and $v' = 1$–4 levels of the *X* and *A* states. This assumption was checked by absolute calibration of the number densities of both states. About 1/3 of the radicals were found in the *A* state.

Exothermic reactions populating excited electronic states have received particular attention because of their potential applications in chemical lasers. The atomic carbon-nitrous oxide reaction $C + N_2O \rightarrow CN(A,X) + NO$ ($\Delta H = -64.9$ kcal/mole) has been shown to form the CN radical in the first two electronic states,[1] $X\,^2\Sigma^+$ and $A\,^2\pi_i$. These states are strongly coupled by rapid collisional energy transfers, with rate constants close to the gas kinetic value[2] even for rare gases, making difficult the determination of the nascent populations in flowing apparatus. These fast energy transfers led us to suggest[3] that $CN(X\,^2\Sigma^+)$ is predominantly formed in highly excited vibrational levels, namely, $v'' = 9$–10, with no or little energy released on the $v'' = 0$ level. In a second step, $CN(A\,^2\pi)$ is populated by energy transfers from isoenergetic $X\,^2\Sigma^+$ levels. In this letter, we show that a global equilibrium exists between the *X*, $v'' = 4$–6, and *A*, $v' = 1$–4 levels for CN densities of about 10^{12} radicals/cm^3. As a consequence of the previously mentioned reaction scheme, and of slow vibration-translation deactivation rates of high lying vibrational states,[4] the *A* state appears to be notably populated.

Atomic carbon was electrically produced in a highly diluted mixture of carbon monoxide in helium. The optimum dilution ratio was obtained by maximizing the fluorescence signal from the CN(A, $v' = 3 \rightarrow X$, $v'' = 1$) band, and was found to be 6.5×10^{-3}. The discharge was operated at power loadings of 11.8 kJ/mole. Nitrous oxide was injected a few millimeters downstream from the cathode. Here again, the optimum N_2O flow rate was derived by maximizing the fluorescence signal, and found to be 1.7 times the CO flow rate. Total flow rates are then He:16.6 μmol/s, CO:110 μmol/s, and N_2O:186 μmol/s, and the pressure in the cell is 3.5 Torr with the discharge on. The static temperature was assumed equal to the rotational temperature. From laser-induced measurements on levels $v'' = 0$ and 1 we obtained a rotational temperature of 330 K. The flow velocity is then 680 m/s (area duct 1.43 cm^2).

$CN(A\,^2\pi)$ relative vibrational populations are measured by detecting the chemiluminescence at right angle from the flow 25 mm downstream from the N_2O injection (transit time: 37 μs). The fluorescence is viewed through a monochromator (1.5 or 0.63 μm blaze grating) equipped with an

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