Tunable ArF* excimer-laser source

J. C. White, J. Bokor, R. R. Freeman, and D. Henderson

Bell Laboratories, Holmdel, New Jersey 07733

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A tunable ArF* (193-nm) excimer source is described that produces over 125 mJ/pulse (peak) at 10 pulses/sec. This device has a spectral width of less than 2 cm^{-1} and a demonstrated tunability of nearly 320 cm^{-1} from 192.8 to 193.9 nm. Tunability, bandwidth, and mode control are achieved by injecting the fourth anti-Stokes line (in H_2) of a frequency-doubled dye laser into an ArF* excimer-amplifier system.

Since the advent of commercially available ArF* excimer lasers, workers in laser spectroscopy and nonlinear optics have been drawn to the high-peak power (>10 MW) and short-wavelength nature (193 nm) of the emission. However, the difficulty in controlling the spectral- and spatial-mode qualities of these lasers has hampered their widespread application. Hargrove and Paisner[1] have constructed a narrow-band (0.25-cm^{-1}), nearly diffraction-limited ArF* oscillator–amplifier system, but continuous tuning of the device was inconvenient since four separate interacting dispersive elements were inserted in the oscillator cavity. Significantly broader-bandwidth, but more conveniently tuned, ArF* systems have been constructed[2] and applied in a variety of spectroscopic and photochemical studies.[3,4] Ideally, one would like to use an injection technique similar to the one applied so successfully in the KrF*-laser system,[5] but, because of the lack of an appropriate nonlinear crystal to produce 193-nm radiation from a tunable dye laser, this method has not been applied to ArF*.

In this Letter we report the wavelength, bandwidth, and spatial-mode control of an ArF* excimer laser by using a 193-nm injection signal derived by Raman scattering using the fourth anti-Stokes line in H_2 of a doubled dye laser, a scheme originally proposed by Hargrove and Paisner.[1] The basic laser system is illustrated schematically in Fig. 1. A pulsed dye laser, operating at approximately 568 nm, is doubled in a KDP crystal. This radiation is converted to approximately 193 nm as the fourth anti-Stokes line in a H_2 Raman cell. The 193-nm signal is injected into an ArF* preamplifier and then into an ArF* amplifier. The output wavelength is found to tune over the gain bandwidth of the ArF* amplifier with a peak output energy of 125 mJ/pulse.

The dye laser used for this work is a commercial pulsed dye-laser system (Quanta-Ray PDL-1A) operating at 10 pulses/sec, with a measured bandwidth of 0.5 cm^{-1}, a pulse length of 5 nsec, and an output energy of approximately 60 mJ/pulse. (We found substantial bandwidth increases when the dye laser was pumped sufficiently hard to obtain its maximum output energy of 100 mJ/pulse.) This radiation was doubled in an angle-tuned KDP crystal, yielding nearly 15 mJ/pulse. Both the doubled light at 284 nm and the fundamental light at 568 nm were loosely focused into a H_2 Raman cell at 388×10^3 Torr (75 psi). The energy of the fourth anti-Stokes line at 19 nm was found to be nearly 50 μJ/pulse when both the fundamental and the doubled light were focused into the cell and less than 10 μJ/pulse when only the doubled light was present as an input to the Raman cell.[6] The output pulse at 193 nm was directly measured to be 2 nsec in duration, on the average, with individual pulses having sharp (<0.5-nsec) spikes on a 2-nsec pedestal. This radiation was injected into a commercial ArF* laser (Lamda-Physik Model EMG 101) operated without reflecting mirrors. As is shown in Fig. 1, this laser was double passed; the output after the second pass had a pulse energy of approximately 10 mJ/pulse, with a pulse width nearly unchanged from the input. The output from the EMG 101 was directed into a second ArF* laser (Lamda-Physik Model EMG 200), also operated without end mirrors. The output energy of this system was measured to be 125 mJ/pulse at the peak of the ArF* gain, with some pulse broadening to approximately 3–4 nsec.

The effective laser bandwidth of the system was measured by monitoring two-photon laser-induced fluorescence in Kr.[4] The unfocused output radiation was directed into a cell containing Kr at several Torr. As the laser was scanned across the Kr [4p(5)6p] two-photon resonance at 103363 cm^{-1}, the resulting Kr

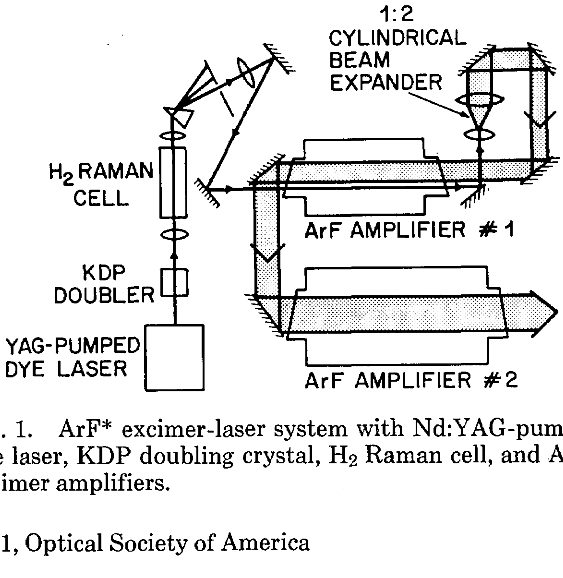

Fig. 1. ArF* excimer-laser system with Nd:YAG-pumped dye laser, KDP doubling crystal, H_2 Raman cell, and ArF* excimer amplifiers.

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[4*p*(5)6*p*–4*p*(5)5*s*] fluorescence at 428.4 nm was detected at right angles by a phototube with a 100-Å bandpass filter. The results of such a measurement are shown in Fig. 2. We measured a two-photon laser-induced fluorescence linewidth of 1.2 cm^{-1}, indicating an actual system bandwidth of approximately 1.6 cm^{-1}. The bandwidth of the doubled dye laser is only 1 cm^{-1}, and we believe that the increased bandwidth arises primarily from saturation of the final ArF* amplifier. (The anti-Stokes Raman-scattering process has been shown not to contribute to the broadening.[7]) As the dye-laser oscillator was pumped by progressively less energy, its linewidth decreased, and the bandwidth of the ArF*-laser system decreased proportionately. In the present configuration the input bandwidth could not be decreased arbitrarily (for example, by inserting an ètalon in the oscillator) because of threshold power requirements for production of the fourth anti-Stokes line of the doubled dye laser. Nevertheless, if a narrow-bandwidth dye-laser system with sufficient energy were used as input, then nearly transform-limited outputs should be obtainable from this system.[5]

The observed output energy versus wavelength is shown in Fig. 3. The source tunes across the entire ArF* gain curve; the dips in the output energy are due to absorptions in atmospheric O_2.[8] These holes in the energy spectrum could be eliminated by enclosing the beam paths and purging with an appropriate nonabsorbing gas (e.g., He) in order to displace the O_2.

No quantitative measure of the mode characteristics of the ArF* source were made except to note that, when the output was directed through a 0.5-m lens, a breakdown in air of over 5 cm in length was obtained. Preliminary measurements of the Raman-scattering efficiency of this source have been performed; greater than 10% conversion of 193 nm to the first Stokes line at 205 nm in 6.33 kg/cm^2 4.65×10^3 Torr (90 psi) of D_2 has been obtained. Such efficiency indicates that the divergence of this source is perhaps a few times diffraction limited.[1] We believe that peak power densities of greater than 10^{11} W/cm^2 and peak energy densities of 10^3 J/cm^2 are routinely realizable.

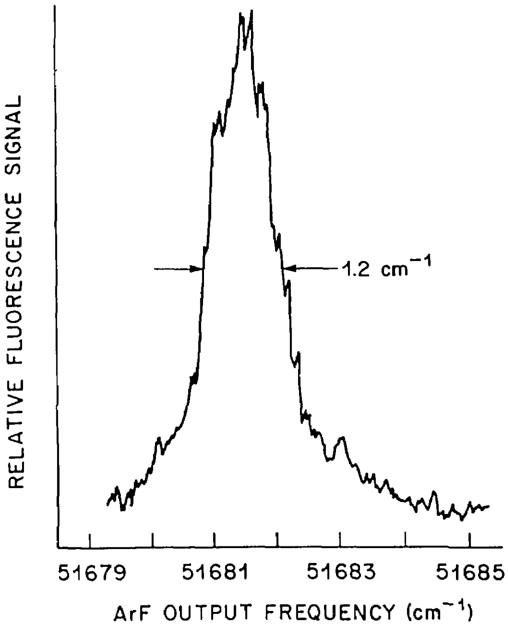

Fig. 2. Relative Kr [4*p*(5)6*p*–4*p*(5)5*s*] fluorescence signal at 428.4 nm as a function of the ArF*-laser tuning. This fluorescence results from the two-photon excitation of the Kr [4*p*(5)6*p*] state at 103363 cm^{-1} and serves as a convenient measure of the bandwidth of the ArF* source.

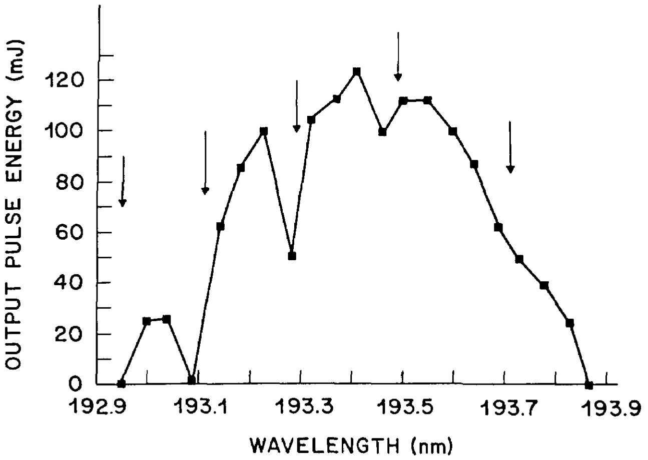

Fig. 3. ArF* output energy as a function of wavelength. The dips in the output are due to atmospheric O_2 absorptions[8] and could be eliminated by using properly purged beam lines.

In conclusion, we have described a relatively simple method of obtaining a controlled-bandwidth, tunable, high-brightness ArF*-laser source. This method uses Raman scattering of dye-laser radiation to produce the radiation at 193 nm. The high-energy (125 mJ/pulse), high-repetition rate (10 pulses/sec), controlled bandwidth ($\sim$1.6 cm^{-1}), and low divergence of this source should permit many interesting applications in nonlinear optics, spectroscopy, and photochemistry.

References

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