Sum-frequency generation of continuous-wave light at 194 nm

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Over 2 mW of continuous-wave tunable 194-nm light is produced by sum-frequency mixing approximately 500 mW of 792-nm and 500 mW of 257-nm radiation in beta-barium borate (BBO). The powers in both fundamental beams are enhanced in separate ring cavities whose optical paths overlap in the Brewster-cut BBO crystal. Due to the higher circulating fundamental powers, the sum-frequency-generated power is nearly 2 orders of magnitude greater than previously reported values. © 1997 Optical Society of America

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Tunable narrowband sources of ultraviolet radiation have applications in laser cooling and in spectroscopy of atoms and molecules. In particular, light at 194.1 nm drives the $5d^{10}6s\ ^2S_{1/2}$–$5d^{10}6p\ ^2P_{1/2}$ resonance in singly ionized mercury. This allows laser-cooling, Raman-cooling, double-resonance experiments and other experiments on strings of electromagnetically trapped Hg^+ ions.[1,2] Because available nonlinear materials cannot be phase matched for second-harmonic generation (SHG) to 194 nm,[3] light at this wavelength is produced by sum-frequency generation (SFG). Also, because most materials absorb in the ultraviolet, only a few crystals are suitable for generation of light in this region. Previously, several microwatts of continuous-wave 194-nm radiation have been produced by SFG in potassium pentaborate (KB5)[4] and 31 μW in beta-barium borate (BBO).[5] Here we report the generation of over 2 mW of coherent cw radiation at 194 nm.

Figure 1 shows an overview of the apparatus. As in Refs. 4 and 5, the wavelengths of the fundamental beams are 792 and 257 nm, where the 257-nm light is produced by frequency doubling the 515-nm light from a single-frequency argon-ion laser. The fundamental beams are enhanced in separate resonant cavities whose smallest waists overlap. At this intersection, the beams propagate collinearly in a

Brewster-cut, angle-tuned BBO crystal to produce the sum-frequency-generated 194-nm radiation.

Light at 515 nm is provided by an argon-ion laser made to run at a single frequency by a temperature-tuned intracavity étalon. An active servo adjusts the temperature of the étalon to maintain maximum power, which eliminates mode hops. Feedback to the position of a piezo-mounted cavity mirror stabilizes the laser frequency relative to a low-finesse reference cavity, reducing short-term fluctuations to less than 1 MHz. Long-term drift is removed by feedback to the reference cavity length so that the laser frequency maintains resonance with a hyperfine feature in molecular iodine.[6]

The 515-nm beam is mode matched into a power enhancement cavity in which a 3 mm × 3 mm × 5 mm, angle-tuned, Brewster-cut BBO crystal is placed. The cavity consists of two 10-cm radius of curvature mirrors, a 30-cm radius of curvature mirror, and a flat input coupler that transmits 1.8% of the input power. The round-trip length of the cavity is 1.35 m, and the 28-μm minimum beam waist is between the two 10-cm mirrors. The crystal is heat sunk when pressed into a slot in an aluminum block. Thin indium foil is placed between the crystal and the aluminum to ensure good thermal contact. The crystal is placed at the 28-μm waist so that the fundamental beam propagates as an *o* wave for type I phase matching. A dichroic beam splitter reflects 97% of the harmonically generated 257-nm light while transmitting the 515-nm light. The cavity is locked to resonance with the incident radiation by use of the Hänsch–Couillaud method,[7] as are all other cavities in this experiment. With the crystal in
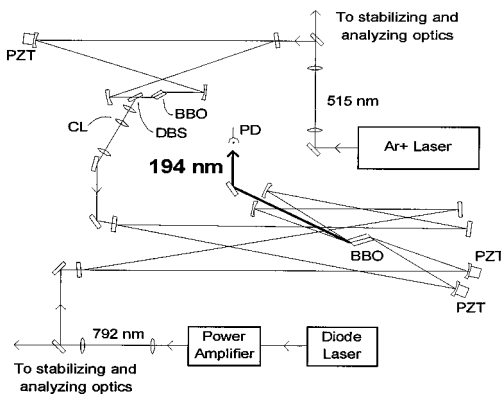
Fig. 1. Optical layout. DBS, dichroic beam splitter; CL, cylindrical lens; PD, photodiode; PZT, piezoelectric transducer. Not shown are optics and electronics for stabilizing and analyzing laser frequencies or for stabilizing enhancement cavities.

place and at low circulating powers, the power enhancement factor is 120.

However, with an incident power of 2 W, the enhancement is reduced to roughly 90 because of nonlinear conversion loss. As the circulating power increases, fractionally more of the fundamental power is transferred to the second-harmonic beam. This increases the cavity losses, lowering the power enhancement factor. Consequently, the overall conversion efficiency $\varepsilon = P_{257}/P_{515}$, where P_{515} is the input power at 515 nm and P_{257} is the output power at 257 nm, does not increase linearly with the input power. Rather, it is determined by[8,9]

$$\sqrt{\varepsilon} = \frac{4T\sqrt{\eta P_{515}}}{[2 - \sqrt{1 - T(2 - L - \sqrt{\varepsilon \eta P_{515}})}]^2}, \quad (1)$$

where T is the transmission of the input coupler, L is the round-trip loss not including conversion losses, and η is the single-pass efficiency of the crystal measured at low powers. Figure 2 shows the theoretically expected values of ε as a function of input power, along with our measured values of ε, corrected by the Fresnel loss of the second-harmonic beam at the exit face of the crystal. For 5.6 W of input power we
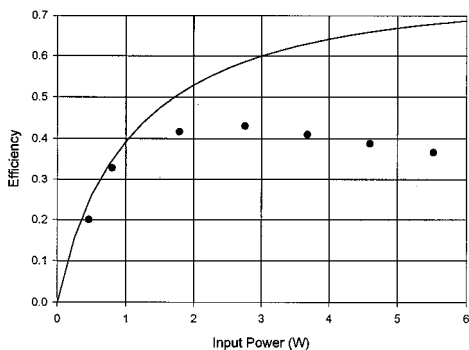

Fig. 2. Theoretically expected values of SHG efficiency from Eq. (1) (solid curve) and measured values (filled circles). Calculated values use $\eta = 6.0 \times 10^{-5}$ W^{-1}, $L = 0.007$ m, and $T = 0.015$.

obtain 2.0 W of second-harmonic radiation. The measured efficiencies, however, are significantly lower than the theoretical values for input powers of 2 W and greater.

This discrepancy is explained by the small, but finite, absorption of the harmonically generated UV light. As more 257-nm radiation is generated, the crystal develops an anisotropic temperature gradient that is due to the nonuniform intensity distribution of the harmonic power. Because the indices of refraction are temperature dependent, a thermal lens is created in the crystal. This changes the mode-matching efficiency between the input beam and the cavity, which decreases the circulating power.[10] The resulting feedback between the intracavity power and the thermal lens can in turn destabilize the cavity resonance.[8] The heat sink controls the crystal temperature sufficiently so that the cavity can be tightly locked with at least 6 W of input power. However, because the heat sink does not eliminate the thermal lens, our optimum conversion efficiency is limited to 40%.

Approximately 500 mW of 257-nm radiation is mode matched into a second power enhancement cavity containing a second, angle-tuned BBO crystal used for SFG to 194 nm. Because the 257-nm radiation is generated in angle-tuned BBO, its beam profile at the crystal surface is approximately rectangular along the walk-off direction.[8,11] The beam's width is the walk-off distance ρl, where ρ is the walk-off angle and l is the length of the crystal. Because the overlap of this beam profile with a Gaussian distribution of width $w_0 = 1/2\rho l$ is[12]

$$\xi = \left[\int_{-w_0}^{w_0} \left(\frac{2}{\pi w_0} \right)^{1/4} \exp\left(-\frac{x^2}{w_0{}^2} \right) \sqrt{\frac{1}{2w_0}}\, dx \right]^2 = 0.89, \quad (2)$$

the second-harmonic beam can be mode matched with as much as $\xi = 89\%$ efficiency into a cavity with spherically symmetric Gaussian modes. After passing through suitably chosen spherical and cylindrical mode-matching lenses, approximately 85% of the input beam is coupled into the enhancement cavity's TEM$_{00}$ mode.

The 257-nm power enhancement cavity is formed by two 30-cm radius of curvature mirrors and two flat mirrors, which includes a 9% transmitting input coupler. The round-trip length is 1.79 m and the minimum waist, located midway between the two curved mirrors, is 39 μm. The power enhancement factor of the empty cavity is approximately 27. When the Brewster-cut BBO crystal is positioned at the cavity waist so that it is near Brewster's angle, the build-up factor can be as great as 21. Due to gradual UV-induced degradation of the cavity surfaces, the build-up factor at the time of this measurement was roughly 12. With 500-mW input, then, the circulating 257-nm power is 6 W.

As in the SHG cavity, the high power and intensity of the circulating 257-nm radiation (>240 kW cm^{-2} for 6-W circulating power) has several adverse effects

on the 257-nm enhancement cavity. Thermal lensing in the SFG BBO crystal destabilizes the intracavity power as explained above. The baseline of the Hänsch–Couillaud dispersion signal also drifts significantly. This may be due to the increased intensity of reflected higher-order cavity modes combined with slight beam misalignments. It is also possible that changes in the crystal birefringence slightly alter the polarization of the light reflected from the cavity. Changes in the crystal's indices of refraction also alter the phase-matching conditions for SFG. Thus the difference in the 194-nm beam position when the cavity is locked into resonance versus when it is swept through resonance is roughly 3 mrad. The beam also moves as the crystal temperature fluctuates over the course of the day. These problems are reduced greatly when the SFG crystal is heat sunk in the same way as the SHG crystal, although the 257-nm intracavity power can still vary by more than 10% over tens of minutes.

Approximately 500 mW of narrowband single-frequency radiation at 792 nm is produced by a master oscillator power amplifier system.[13] The master laser is an external-cavity diode laser in the Littman configuration, whose free-running line width is less than 0.5 MHz. The frequency of the master laser is stabilized to an external cavity whose length is servoed to light from the iodine-stabilized argon-ion laser. Approximately 18 mW from the master laser are mode matched into a tapered amplifier[14] acting as a slave laser. With no more than 1.1 A into the slave laser, as much as 600 mW can be generated safely. We verified that the frequency of the slave laser is phase locked to the master laser with as little as 3 mW of injected power. The shape of the slave laser beam is transformed so that it is nearly spherically Gaussian, after which the beam is mode matched into a power enhancement cavity with greater than 90% efficiency.

The 792-nm enhancement cavity is formed by two 30-cm radius of curvature mirrors and two flat mirrors. The round-trip length of the cavity is 1.83 m, and the minimum cavity waist size is approximately 68 µm. The transmission of the input coupler is 1.5% and the build-up factor of the empty cavity is approximately 80. With the crystal placed near the cavity waist so that its surfaces are at Brewster's angle, the power enhancement is reduced only slightly. Thus for 600-mW input power, the circulating power is 48 W. Aside from a 10% decrease in intracavity power when the 257-nm cavity is locked to resonance, the 792-nm cavity is not affected by thermal lensing in the crystal at these powers.

The 792-nm and 257-nm cavities are situated so that the intracavity beams coincide at the crystal position near the minimum beam waists. The Brewster-cut SFG BBO crystal is 4 mm × 4 mm × 5.75 mm, and cut at 71.6° to the optic axis. Both fundamental beams propagate as o waves inside the crystal, while the SFG beam propagates as an e wave. To make the beams collinear inside the crystal, the incidence angles of the fundamental beams at the crystal are adjusted to account for the difference in refraction angles. Only the 792-nm beam is strictly at Brewster's angle. Because of the differences in refraction angles of the SFG and fundamental beams, the 194-nm beam is separated sufficiently from the 792-nm and 257-nm beams to pass the cavity optics easily. For the conditions described here, a National Institute of Standards and Technology calibrated photodiode measures 1.4 mW of 194-nm radiation 2.0 m from the crystal. If absorption in air and the Fresnel loss at the exit surface of the crystal are accounted for, approximately 2.2 mW of radiation is generated.

To conclude, we have produced more than 2 mW of 194-nm radiation, which is 2 orders of magnitude greater than previously reported. This is due partly to production of 500 mW of 257-nm radiation by SHG in BBO, whereas previous experiments produced only 20–30 mW by SHG in ammonium dihydrogen phosphate (ADP).[4,5] Furthermore, although the quality of the 257-nm power enhancement cavity is not improved over that reported in Ref. 5, the build-up factor of the 792-nm power enhancement cavity is seven times that of Refs. 4 and 5. The 194-nm power may still be increased by approximately a factor of 3 when the intracavity beam waist sizes are decreased closer to the optimum size of approximately 15 µm[11] and when the build-up factor of the 257-nm power enhancement cavity is increased. However, the higher intensities (especially at 257 nm) might cause crystal damage or severe thermal problems.

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