Efficient ir image up-conversion in two-photon resonantly pumped Cs vapor*

E. A. Stappaerts,† S. E. Harris, and J. F. Young

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305
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Resonant two-photon pumping in the Cs $6s\,^2S$-$7s\,^2S$ transition has been used for 2.9 μm to 4550 Å image up-conversion. A power conversion efficiency of 20% with 1000 resolvable spots was achieved using a pump power of 8 kW. The pumping laser, Nd:lanthanum berylate, has a natural two-photon coincidence with the Cs $6s\,^2S$-$7s\,^2S$ transition.

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We have used two-photon resonantly pumped mixing in Cs vapor to up-convert 2.9-μm images to 4550 Å; a power conversion efficiency of 20% with 1000 resolvable spots was achieved using a pump power of 8 kW. The process makes use of a resonantly enhanced third-order nonlinearity achieved by two-photon pumping the nonallowed Cs $6s^2S$-$7s^2S$ transition. Resonant two-photon pumping of nonallowed transitions has been used previously for the generation of tunable uv radiation,[1] and the theory of such interactions has been examined by Harris and Bloom,[2] Stappaerts,[3] and Stappaerts *et al.*[4] Single resolution element ir up-conversion of CO_2 laser radiation in Na vapor has been demonstrated by Bloom *et al.*[5]

Figure 1 shows the energy-level diagram of our Cs image converter system. Use of the nonallowed Cs 6s-7s transition is especially attractive because of the natural two-photon coincidence with the wavelength of the Nd:lanthanum berylate solid-state laser.[6] All of the previously reported two-photon resonantly pumped up-converters have required a tunable laser source. In addition, the efficiency is a maximum for ir wavelengths in the 3-μm atmospheric window, corresponding to the Cs $7s^2S$-$7p^2P^0$ interval.

A schematic of the imaging experiment is shown in Fig. 2. The flash-lamp-pumped electro-optically Q-switched $Nd{:}La_2Be_2O_5$ laser produces about 35 kW in a 100-ns pulse at 1.0790 μ, using an x-axis rod with the radiation polarized along the y (or crystallographic b) axis.[6] An internal etalon of 10-cm^{-1} free spectral range and a finesse of 9 is used to narrow the laser bandwidth to ~0.1 cm^{-1} and to tune the laser into exact correspondence with the Cs 6s-7s transition. About 25% of the laser output is split off, expanded to an area of 0.1 cm^2 (8×10^4 W/cm^2), and is used as the up-converter pump. The remaining beam, doubled in temperature-tuned CsD_2AsO_4, pumps a $LiNbO_3$ parametric oscillator providing the 2.9-μm illuminating signal. The ir beam is spatially filtered, expanded to a diameter of about 3 cm, passed through the object, and combined with the pump beam before entering the Cs cell. The up-conversion is done in the Fourier mode[7]; the 20-cm lens L_1 produces the Fourier transform of the 2.9-μm object space in the up-converter, and the 50-cm lens L_2 reconstructs the up-converted 4550-Å Fourier components onto 3000 ASA Polaroid film. The resultant image/object size is 0.4.

The Cs is contained in a 2-mm-long side-arm cell with sapphire windows. The Cs number density is controlled by maintaining the side-arm temperature at about 360 °C, while the windows and main body are superheated an additional 60 °C to eliminate vapor condensation. By measuring the absorption width of the self-broadened resonance line we estimated a Cs density of 1.4×10^{17} cm^{-3}. This agrees resonably well with the temperature as measured on the outside of the cell. Although window damage *per se* is not a problem, the sapphire-metal seals have proved quite unreliable and short lived.

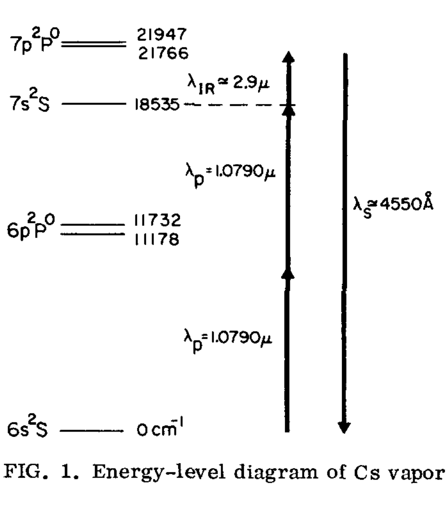

FIG. 1. Energy-level diagram of Cs vapor up-converter.

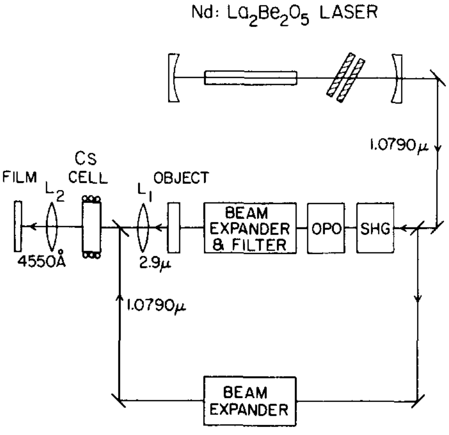

FIG. 2. Schematic of the ir image up-converter. A portion of the laser output, doubled in CsD_2AsO_4 (SHG), pumps a $LiNbO_3$ parametric oscillator (OPO) providing the 2.9-μm illuminating beam.

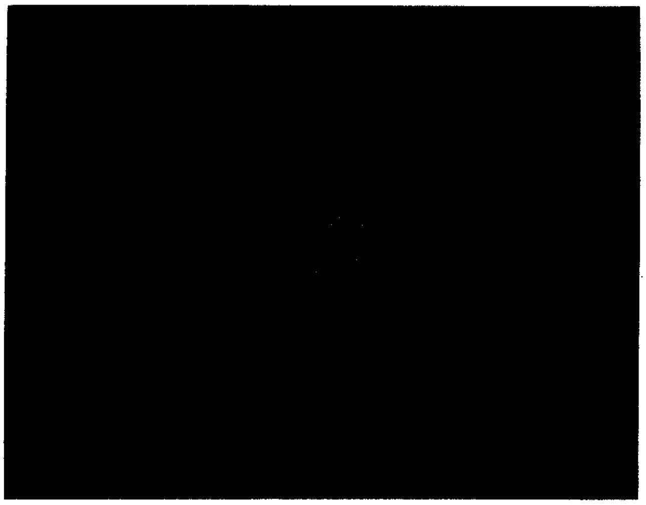

FIG. 3. Up-converted image. We estimate that the original photograph consists of at least 1000 resolvable spots.

The field of view of the up-converter is determined by the ir $\bar{k}$-vector angle which produces a phase mismatch of π. For a collinear interaction length of L, the solid angle acceptance is $\Omega = \pi\lambda_{\text{ir}}/L = 5$ msr, or a full cone angle of about 4.6°. Thus, the theoretical number of resolvable spots is $R = A\Omega/2\lambda_{\text{IR}}^2 = 2\,780$ for our pump area $A = 0.1$ cm^2.

Object grids were constructed of black tape on a quartz slide. Figure 3 shows an up-converted image made with tape 0.25 mm wide. In the original photograph these stripes are sharp and well resolved, and we estimate that the image field consists of at least 1000 resolvable spots. The intensity nonuniformity is caused by spatial variations in the pump and illuminating beams, as well as in the filters and optical components.

Careful conversion efficiency measurements were made by placing a small heat-pipe Cs cell in the experimental configuration of Fig. 2 and measuring the 2.94 μm and 4558 Å powers directly with a pyroelectric detector. The conversion efficiency was 84% for a cell $(NL)^2$ product four times larger than that used for the imaging cell. Measurements using the imaging cell could not be made because of a cell failure, but based on measured power densities and the heat-pipe data we estimate the efficiency to be 20%. This is about a factor of 3 lower than predicted by the plane-wave theory of Ref. 3 and is probably due primarily to uncertainties in Cs density, as well as imperfect pump and ir beam overlap, and a nonuniform pump power density.

For vapor-phase image up-converters of this type the product of the efficiency and the square of the resolution is independent of the interaction length[3]; thus, phase matching over a long cell does not improve the device performance relative to a cell one coherence length long. For experimental convenience, however, we used a long cell and phase matched the up-conversion process by adjusting the ir wavelength. This is possible because the k-vector mismatch, $\Delta k = k_s - 2k_p - k_{\text{ir}}$, is dominated by the frequency difference between the sum signal and the Cs $6s$-$7p$ interval. Equally important, however, a small population in the $7s$ level, due to two-photon absorption of the pump, can significantly affect the ir index of refraction and thus Δk. Stappaerts[3] has shown that the self-phase-matching detuning can be expressed as $\Delta\tilde{\nu} = 16.3 - 970(N_{7s}/N_{6s})$, where $\Delta\tilde{\nu}$ is the difference in cm^{-1} between the $7s$-$7p$ transition and the ir, and N_{7s}, N_{6s} are state population densities. Experimentally, we observe a maximum signal for a detuning of about 9 cm^{-1}, indicating that $N_{7s}/N_{6s} \simeq 0.75\%$, in good agreement with our estimates. We note that systems using fixed-frequency ir illumination, such as an HF laser, could be phase matched by using an off-angle interaction or by adding a compensating dispersive vapor.[8,9]

These initial experiments have shown that two-photon resonantly pumped vapor up-converters can provide useful efficiency and resolution with moderate pump powers. Additional attractive features include scalability to large apertures, the ability to withstand high power densities, and low loss throughout the ir. A disadvantage, relative to nonlinear crystal systems, is the dependence of conversion efficiency on the square of the pump power, effectively restricting the vapor systems to pulsed operation. Thus, although the efficiencies are high, the low duty cycle will probably limit these devices to active, illuminated imaging.[10]

The optimum design of these up-converters is discussed more fully by Stappaerts[3] with respect to a number of limiting processes. He calculates, for example, that a 2.9 μm → 4550 Å up-converter 7 mm long, 13 cm^2 in area, and operating at a Cs density of 3×10^{17} cm^{-3} should achieve 10^5 resolvable spots at a photon efficiency of 28% for a pump power of 0.5 MW. A $LiNbO_3$ up-converter having the same performance would require 350 times more pump power. Thus, it seems likely that the $Nd{:}La_2Be_2O_5$-Cs $6s$-$7s$ coincidence will lead to a number of practical devices.

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†Present address: Northrup Corporation, 3401 West Broadway, Hawthorne, Calif. 90250.

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