the 12-μm output power as a function of NH_3 pressure. The optimum NH_3 pressure is found to be ~ 475 mTorr, close to the value of 450 mTorr which gives the peak small signal gain calculated from the average longitudinal pump intensity.[5] The maximum operating pressure is limited by the strong absorption of the pump radiation by the pressure broadened sR (5,0) transition. At 1 Torr, this effect reduces the average pump intensity to $\sim 1/3$ of the value in the evacuated capillary tube. In addition, we studied the influence of buffer gases, as these have been shown to be useful in previous work.[7] Contrary to the results of Julien *et al.*,[8] we found that mixtures of NH_3 with He or N_2 did not increase the 12-μm output power. The difference in these two experiments is probably explained by the fact that wall cooling dominates in our waveguide cell, while Julien *et al.* required a low mass buffer gas to improve the thermal conductivity of NH_3 in an open resonator.

Similar results have been observed with shorter waveguide cells. A 60-cm-long, 2.5-mm bore capillary tube gave peak output powers of 5.3 and 7.3 W at room and dry ice temperatures, respectively, while lasing has been observed in 1.5-mm bore tubing and in tubes as short as 15 cm. The shorter tubes are much easier to align and optimize than the 1.2-m tube, but do not give as much output power.

In conclusion, we have obtained 10.2 W from a 12.08-μm Raman laser operating at the highest known efficiency for a cw optically pumped infrared laser. The cavity design is very simple and versatile, and can be utilized for other optically pumped mid-infrared lasers.[3]

This work was supported, in part, by the Natural Sciences and Engineering Research Council, Canada. We wish to thank D. Kroeker for the construction of the CO_2 laser, and P. E. Jessop, H. D. Morrison, and L. Sinclair for useful discussions.

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[11] Measured transmission: 98% at 12.08 μm and 88% at 9.22 μm.

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[13] A decrease in optimum pressure from ~ 450 mTorr ($T = 300$ K) to ~ 350 mTorr ($T = 200$ K) is predicted from small signal gain calculations. The threshold pump power was further reduced to 1.8 W when the 28% output coupler was replaced with a dichroic minor reflecting 97% at 12.08 μm.

[14] The remainder is reflected from the input mirror and the AR coated ZnSe. Fabry–Perot effects in the present cavity are negligible.

[15] It is significant to note that the average 9-μm intensity in the cavity under cw lasing conditions can be as much as five times the pump intensity required to achieve threshold. This result indicates that pump defletion is not the dominant mechanism leading to the reduction of the 12-μm gain.[8]

Multicolor passive (self-pumped) phase conjugation

Mark Cronin-Golomb, Sze-Keung Kwong, and Amnon Yariv
California Institute of Technology, Pasadena, California 91125

(Received 29 December 1983; accepted for publication 7 February 1984)

Passive phase conjugation of up to six lines (457, 476, 488, 496, 501, and 514 nm) of the all lines output of an argon ion laser is reported. Imaging characteristics and reflectivity measurements are given. In general, multiline operation results in some loss in both reflectivity and image resolution. This work opens the possibility for passive phase conjugation of full color images.

PACS numbers: 42.65. – k, 42.60.He, 42.30.Va, 42.78.Cf

The recently demonstrated self-pumped photorefractive phase conjugate mirrors have already been shown to possess several attractive features, including high reflectivity and operation over a wide range of wavelengths for milliwatt level beams.[1–8] In this letter we report that they are also capable of phase conjugating several laser lines simultaneously; this development leads to the possibility of self-pumped conjugation of full color images. Using all lines output from an argon ion laser we have observed simultaneous reflection of up to six different lines: 457, 476, 488, 496, 501, and 514 nm in both the ring[5] and semilinear[3] mirrors. The devices generate their own pumping beams so that no *a priori* knowledge of the spectral components of the incident laser beam is required, thereby removing one of the problems associated with previous multiline photorefractive phase conjugation, where the pumps had to be supplied externally.[9]

The imaging characteristics of the semilinear mirror were investigated with the apparatus shown in Fig. 1. An Air Force Resolution Chart was illuminated with the all lines output of an argon ion laser. The beam was then loosely focused into a passive phase conjugate mirror comprising a crystal of barium titanate and a 5-cm radius of curvature mirror which started pumping oscillation between itself and the crystal by reflecting and focusing fanning light into the

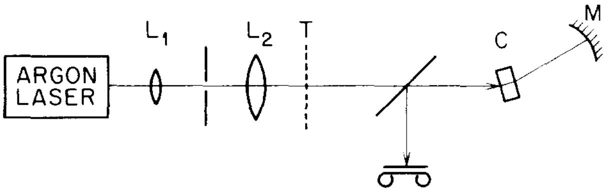

FIG. 1. Apparatus used to demonstrate multicolor passive phase conjugation in the semilinear mirror. Using a cartesian coordinate system with the incident beam traveling along the abscissa, and the coordinates in centimeters the elements are 30× beam expander (79,0); 14-cm focal length lens (61,0); Air Force Test Chart (41,0); beam splitter (13,0); barium titanate crystal (0,0); 5-cm radius of curvature cavity mirror (− 5,0.5). Various different detector arrangements were used to examine the phase conjugate signal: a light meter and a camera, used in conjunction with a grating for dispersing the signal into its spectral components. The crystal measured 5×5×4 mm with its c axis parallel to the 4-mm side, pointing in the direction of the vector (0.18, − 0.98).

crystal. The phase conjugate reflection was picked off by the beam splitter and photographed at the phase conjugate image plane. Figure 2 shows the result when the laser is operated single line at 488 nm. In multiline operation the output is as shown in Fig. 3. Crosstalk between the various holographic gratings has evidently caused some loss of resolution as well as some error in the relative positioning of the various spectral components. Figure 4 shows one corner of the image dispersed by a grating into its five separate frequency components.

Reflectivity data were taken for several beams of varying spectral compositions. In Fig. 5 the data are plotted as a function of fractional beam intensity $F_j = I_j/I_0$, where I_j is the intensity of the jth spectral component in a beam of total intensity I_0. The standard models of the photorefractive effect[10] indicate that the reflectivity R_j should go approximately as F_j^2. This theoretical prediction is also represented in Fig. 5. The more intense components approximately follow the theory, but the other components show discrepancies; their reflectivities are significantly higher than would be expected. This is possibly due to the freedom of the resonator to choose optimum oscillation configurations.

The dependence of the results on wavelength is quite weak, since the spectral response of the crystal is only a slowly varying over the frequency range of interest. This was confirmed by replacing the prismatic frequency selective element in the laser and taking reflectivity data for each of the lines, excited separately. In each case, the reflectivity was about 25%.

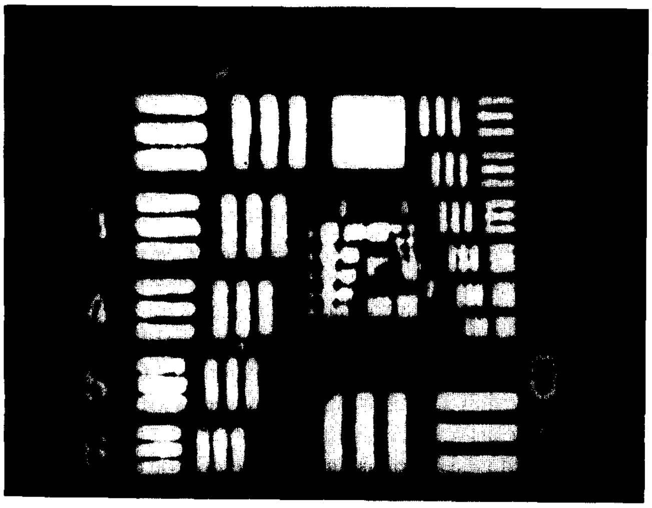

FIG. 2. Phase conjugate reflection produced by the apparatus of Fig. 1 with the laser set for single line output at 488 nm.

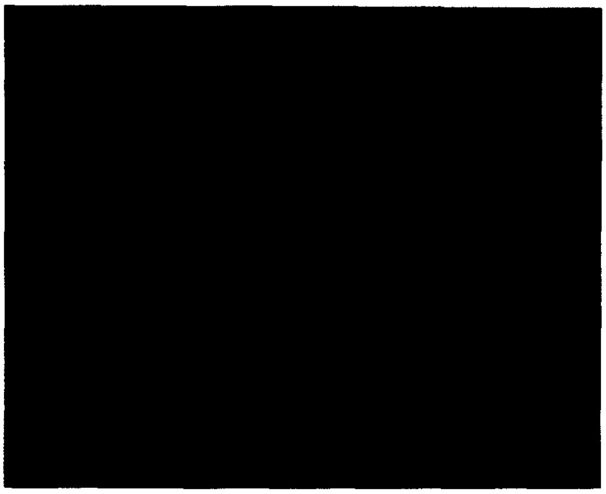

FIG. 3. Phase conjugate reflection produced by the apparatus of Fig. 1 with the laser set for multiline operation.

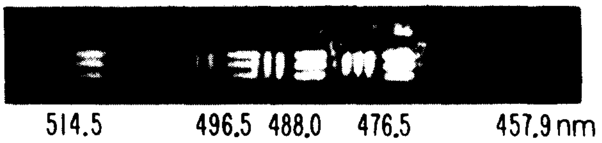

FIG. 4. Lower right-hand corner of the image of Fig. 3 dispersed with a diffraction grating. Five separate frequencies are represented, as indicated.

The rise times of the various spectral components were examined with a digital oscilloscope connected to a computer for data reduction. The holographic gratings were erased by blocking the crystal-curved mirror resonator cavity, and waiting for the oscillation to decay. The cavity was then unblocked, and the rise time of the conjugate reflection in each of the spectral components was recorded. Subsequent analysis indicated that in the intial stages of development the growth was exponential in time. The associated time constants were

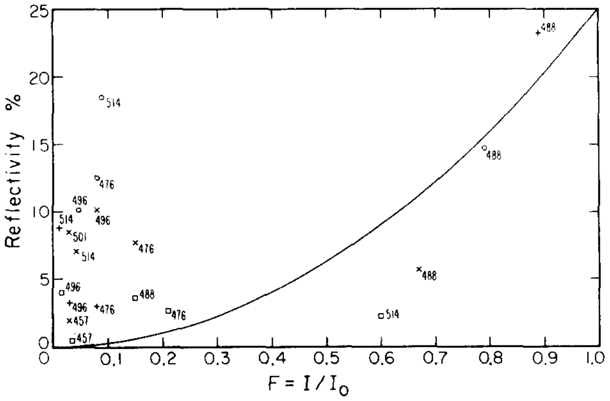

FIG. 5. Phase conjugate reflectivity of a semilinear mirror for four beams of varying spectral composition. Each beam is represented by a different symbol: squares, diagonal crosses, daggers, and circles. The particular wavelengths associated with the individual data points are also given. A theoretical prediction is given by the solid line.

identical for each component, within experimental error: 64 and 210 ms for beams of total intensity I_0 80 and 21 mW/mm^2, respectively. This is in accordance with photorefractive theory which shows that the product of beam intensity and rise time should be constant.

This work was supported by the U. S. Air Force Office of Scientific Research, and the U. S. Army Research Office, Durham, North Carolina.

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80× single-stage compression of frequency doubled Nd:yttrium aluminum garnet laser pulses

A. M. Johnson, R. H. Stolen, and W. M. Simpson
AT&T Bell Laboratories, Holmdel, New Jersey 07733

(Received 22 December 1983; accepted for publication 31 January 1984)

Single-stage compression factors as high as 80× have been demonstrated for the 0.532-μm optical pulses of a frequency doubled Nd:yttrium aluminum garnet laser using a single-mode fiber and a modified grating-pair delay line. Input optical pulses of 33-ps duration have been compressed to 0.41-ps duration. This represents the largest single-stage compression factor reported to date. Subpicosecond optical pulses can be obtained directly from relatively long optical pulses without the use of a mode-locked dye laser.

PACS numbers: 42.80.Mv, 42.65. — k, 42.60.He, 42.60.Fc

The technique of optical pulse compression utilizing self-phase modulation (SPM) to chirp the pulse in a single-mode fiber followed by a grating-pair dispersive delay line has been very successful in compressing dye laser pulses. A 3× single-stage compression of the colliding pulse mode-locked (CPM) laser has resulted in optical pulses as short as 30 fs.[1] A 65× two-stage compression of a synchronously mode-locked dye laser has resulted in optical pulses as short as 90 fs.[2] The key to these results is the realization that group velocity dispersion (GVD) acts to linearize the chirp over most of the length of the pulse, so that almost all the input power appears in the compressed pulse.[3] This results in high quality optical pulses with minimal substructure.

We report an 80× single-stage compression of 240 W, 33-ps duration optical pulses from a cw mode-locked frequency doubled neodymium:yttrium aluminum garnet (Nd:YAG) laser to 1.2 kW, 0.41-ps duration optical pulses. The compression of these 0.532-μm optical pulses has resulted in the largest single-stage compression factor reported to date. These results demonstrate the production of subpicosecond optical pulses directly from relatively long optical pulses without the use of a mode-locked dye laser. Calculations show that it is possible to achieve subpicosecond pulses of high quality starting with pulses as long as 100-ps duration, but that the required fiber length and grating separation increase rapidly with pulse width, and that the optimum pulse shape becomes a sensitive function of peak power, fiber length, and grating separation.[4] Frequency-doubled Nd:YAG pulses are particularly useful for a first investigation of this long-pulse regime because their pulse width and power lead to optimum fiber lengths short enough that fiber absorption does not play a major role and to optimum grating separations which fit conveniently on an optical bench. In addition, the frequency-doubling crystal provides excellent isolation between the Nd:YAG laser and scattered light from the fiber. This high-repetition rate (100 MHz) source of high power optical pulses is directly useful for applications involving subpicosecond pulses in the visible and is a potential pumping source for a large class of visible dyes and a source for generating harmonics in the UV.

The 0.532-μm optical pulses[5] were obtained from a Quantronix 116 cw Nd:YAG laser that was harmonically mode-locked at a modulation frequency of 100 MHz and then frequency doubled in a crystal of $KTiOPO_4$ (KTP). This system is capable of delivering 0.532-μm optical pulses of an average power approaching 1.5 W (455-W peak) at a repetition rate of 100 MHz. We used background-free autocorrelation in a 1-mm piece of KDP to measure optical pulse widths. The autocorrelation half-width of the 0.532-μm optical pulses was 47 ps (Fig. 1). If we assume a Gaussian pulse shape, we obtain a pulse width of 33 ps.

The experimental arrangement for pulse compression is

0003-6951/84/080729-03$01.00