

# High-reflectivity, wide-bandwidth optical phase conjugation via four-wave mixing in potassium vapor

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We report on a high-reflectivity (up to 670%) wide-bandwidth (up to 230 MHz) phase-conjugate mirror formed using backward-four-wave mixing with continuous-wave pump beams in a 2-mm potassium vapor cell. The reflectivities and bandwidths are significantly larger than have been measured previously, and the bandwidth is ten times greater than is predicted theoretically. The reflectivity-bandwidth product is more than an order of magnitude improvement over those previously achieved with other continuous-wave phase-conjugate systems. © 1996 American Institute of Physics. [S0003-6951(96)05135-2]

Optical phase conjugation based on backward-four-wave mixing with continuous-wave (cw) beams has been demonstrated extensively in different nonlinear media including atomic vapors,<sup>1-6</sup> photorefractive materials,<sup>7-9</sup> and semiconductor diode lasers.<sup>10</sup> The goal of these studies is to develop phase-conjugate mirrors (PCMs) for use in practical applications such as optical image processing, optical computing, signal processing, and laser linewidth reduction.<sup>11</sup> To be considered a suitable candidate for use in many of these applications, a PCM must exhibit a high phase-conjugate reflectivity  $R_{pc}$ , a fast time response  $\tau$ , and a large angular acceptance. Typically, a tradeoff exists between achieving a high reflectivity and a fast time response. For example, with photorefractive media, high reflectivities ( $R_{pc} \sim 10^4\%$ ) can be achieved at the expense of a fast time response ( $\tau \sim 1$  s),<sup>8</sup> whereas semiconductor diode lasers offer a fast time response ( $\tau \sim 100$  ps) with a relatively low reflectivity ( $R_{pc} \sim 0.8\%$ ).<sup>10</sup>

In this letter, we report on the properties of a four-wave-mixing continuous-wave PCM formed using an alkali vapor as the nonlinear medium, and we demonstrate that this PCM can exhibit a high reflectivity ( $R_{pc}$  up to 670%) and a fast time response ( $\tau$  as low as 700 ps). The measured reflectivities are a significant improvement over those previously obtained using the two-level nonlinearity (250%)<sup>1</sup> or the optical pumping nonlinearity (350%)<sup>2</sup> in atomic vapors. This improvement results from the use of much higher pump powers than have been used previously<sup>1,2</sup> and from the selection of a relatively thin vapor cell, which allows us to focus tightly over the entire interaction length. The PCM can also exhibit a bandwidth  $\Delta\nu_{pc} (= 1/2\pi\tau)$  as large as 230 MHz, which is greater than the largest bandwidth (25 MHz) that has been previously achieved<sup>4</sup> in an atomic-vapor-based PCM. Our results show that an atomic-vapor-based PCM can achieve an excellent compromise between maximizing the reflectivity and the bandwidth, and we have measured a reflectivity-bandwidth product of  $6 \times 10^8$  Hz that is over an order-of-magnitude improvement over the largest value of the reflectivity-bandwidth product ( $2 \times 10^7$  Hz) previously

measured<sup>4</sup> with a cw PCM. Table I summarizes the reflectivity, bandwidth, and reflectivity-bandwidth product that have been demonstrated with cw PCMs.

We perform optical phase conjugation via four-wave mixing using a frequency-stabilized Ti:S laser (2-W output,  $\lambda_0 = 767$  nm) (Fig. 1). The nonlinear medium is atomic potassium vapor confined in a 2-mm cell that can be heated to 400 °C. The potassium reservoir can be heated to 350 °C. The signal beam and both counterpropagating pump beams are linearly polarized in the same direction. Each pump beam can have up to 600 mW of power, and the diameter of each pump is 240  $\mu\text{m}$  at the cell. The signal beam is much weaker (up to 350  $\mu\text{W}$ ) and has a smaller diameter (120  $\mu\text{m}$ ) at the cell. The short (2 mm) interaction length allows for a relatively large range of angular separations between the signal and forward-propagating pump beam.

We perform aberration correction to verify that the beam generated at the PCM is the true conjugate of the signal beam. Figures 2(a) and 2(b) show the unaberrated signal and conjugate beams, respectively. We impose spatial distortions on the signal wave front by inserting a HF-etched glass aberrator into the signal beam path (Fig. 1). The conjugate beam retains its optical quality [Fig. 2(c)]. As a check, we replace the PCM with an ordinary dielectric mirror and observe that the reflected beam is highly distorted after a double pass through the aberrator and lens [Fig. 2(d)].

The reflectivity is measured by mechanically chopping the signal beam and using lock-in detection. The reflectivity is maximized at a pump detuning that is the best compromise

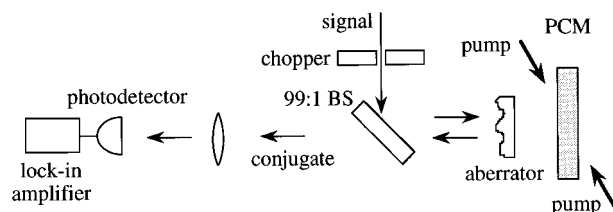


FIG. 1. The experimental setup. BS: beamsplitter; PCM: phase-conjugate mirror.

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TABLE I. A comparison of cw PMCs. The values for K are obtained from the present experiment, and the wavelength ( $\lambda_0$ ), reflectivity ( $R_{pc}$ ), bandwidth ( $\Delta\nu_{pc}$ ), and reflectivity-bandwidth product ( $R_{pc}\times\Delta\nu_{pc}$ ) are shown.

Nonlinear medium	$\lambda_0$ (nm)	$R_{pc}$	$\Delta\nu_{pc}$ (MHz)	$R_{pc}\times\Delta\nu_{pc}$ (Hz)
K ( $N=2\times 10^{14}$ cm $^{-3}$ ) <sup>a</sup>	767	6.7	90	$6\times 10^8$
K ( $N=8\times 10^{13}$ cm $^{-3}$ ) <sup>b</sup>	767	1.4	190	$3\times 10^8$
K ( $N=3\times 10^{13}$ cm $^{-3}$ ) <sup>c</sup>	767	0.4	230	$9\times 10^7$
Na ( $N=2\times 10^{14}$ cm $^{-3}$ ) <sup>d</sup>	589	0.8	25	$2\times 10^7$
AlGaAs diode laser <sup>e</sup>	830	0.008	1000	$8\times 10^6$
Na ( $N=5\times 10^{13}$ cm $^{-3}$ ) <sup>f</sup>	589.6	50	0.1	$6\times 10^6$
BaTiO $_3$ <sup>g</sup>	514.5	100	$2\times 10^{-7}$	16
InP:Fe <sup>h</sup>	1060	0.74	$1.59\times 10^{-6}$	1.18

<sup>a</sup>This work.

<sup>b</sup>This work.

<sup>c</sup>This work.

<sup>d</sup>Reference 4.

<sup>e</sup>Reference 10.

<sup>f</sup>Reference 5.

<sup>g</sup>Reference 8.

<sup>h</sup>Reference 7.

between maximizing the nonlinearity and minimizing the absorption of the pump beams, as shown in Fig. 3(a). Figure 3(b) shows the reflectivity as a function of pump power for three values of the atomic number density. Under conditions in which  $N=3\times 10^{14}$  cm $^{-3}$ , a nonlinear least-squares fit of  $R_{pc}$  to the expression predicted for degenerate-four-wave mixing in an ideal Kerr medium<sup>12</sup> yields  $\chi^{(3)}\sim 10^{-6}$  esu [Fig. 3(b)]. We observe reflectivities as high as 670% under conditions in which  $N=2\times 10^{14}$  cm $^{-3}$ , the detuning  $\Delta$  of the pump beams from resonance is  $-2$  GHz, and the pump intensity is  $10^3$  W/cm $^2$ .

We determine the full width at half-maximum bandwidth ( $\Delta\nu_{pc}$ ) of the PCM from our reflectivity measurements at several values of the signal-pump detuning  $\delta\nu = \nu_{\text{signal}} - \nu_{\text{pump}}$ , where  $\nu_{\text{signal}}$  and  $\nu_{\text{pump}}$  are the optical frequencies of the signal beam and pump beams, respectively. Two acousto-optic modulators that provide frequency shifts of 30–50 MHz and 60–120 MHz are used to shift the signal frequency relative to the pump frequency. From our measurements and by assuming that the reflectivity is symmetric about the pump frequency,<sup>4</sup> we estimate that  $\Delta\nu_{pc}$  is  $90\pm 10$  MHz when  $R_{pc}$  ( $\delta\nu=0$ ) is 670%. The bandwidth increases to 230 MHz ( $\tau=700$  ps) by operating the PCM in a less nonlinear regime ( $N=3\times 10^{13}$  cm $^{-3}$ ,  $R_{pc}\sim 40\%$ ). The 230-MHz bandwidth is a significant improvement over the largest bandwidth of 25 MHz achieved previously<sup>4</sup> in an atomic-vapor-based PCM. The measured bandwidths are also considerably larger than the values predicted by a theory of phase conjugation via nearly degenerate four-wave mixing in a two-level system that assumes the amplitudes of the pump waves are constant<sup>13</sup> even when we include Doppler broadening of the atoms [Fig. 4(a)]. At this time we have not been

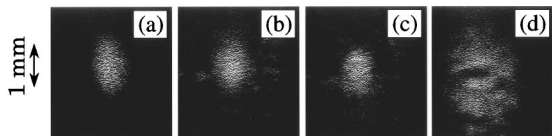


FIG. 2. Demonstration of aberration correction: (a) signal; (b) conjugate; (c) conjugate (aberrator in); (d) retroreflected beam (aberrator in), where  $N=2\times 10^{14}$  cm $^{-3}$ ,  $\delta\nu=109$  MHz,  $R_{pc}\sim 90\%$ , and the laser is tuned 2 GHz below resonance. An approximate scale bar is shown in the figure.

able to reconcile why the measured bandwidths are much larger than the predicted bandwidths. We do observe the trend that the bandwidth decreases as the density increases, as the theory predicts.<sup>13</sup> Note that this trend results from operating in the highly nonlinear regime ( $R_{pc}\geq 100\%$ ) and differs from the behavior one might expect<sup>4</sup> due to the dipole dephasing time  $T_2$  decreasing with increasing density ( $4\text{ MHz}\leq 1/(2\pi T_2)\leq 45\text{ MHz}$ ).<sup>14</sup>

We compare our PCM with other cw PMCs using the reflectivity-bandwidth product,  $R_{pc}\times\Delta\nu_{pc}$ , as a figure-of-merit. Table I summarizes the reflectivity-bandwidth product of other cw PMCs. The reflectivity-bandwidth product of our PCM as a function of the atomic number density is shown in Fig. 4(b). At each density, the bandwidth is measured under the same conditions that maximize the reflectivity. Figure 4(b) shows that the reflectivity-bandwidth product is greater than the largest value of  $2\times 10^7$  Hz previously achieved by

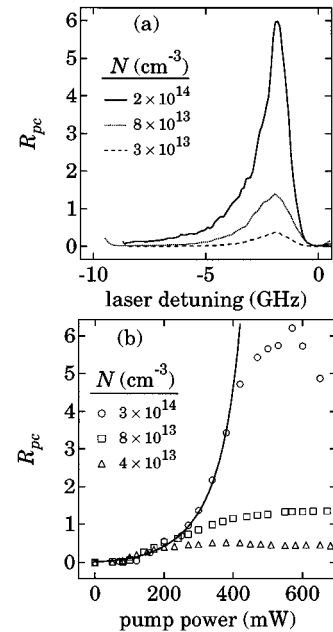


FIG. 3. (a) Reflectivity as a function of pump detuning from atomic resonance and (b) reflectivity as a function of pump power for three values of the atomic vapor density, where the laser is tuned 2 GHz below resonance.

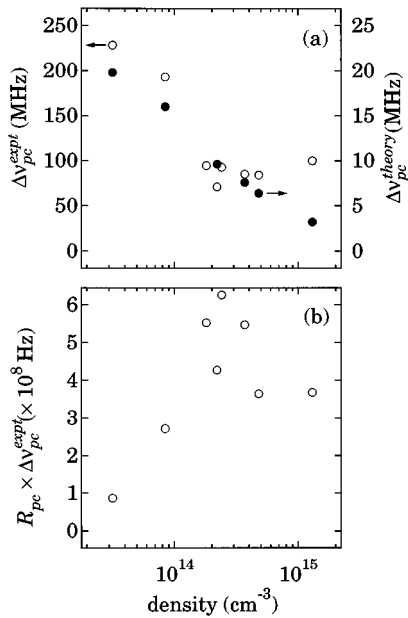


FIG. 4. (a) Measured values of the bandwidth (see the left-hand side axis) with the corresponding theoretically predicted values of the bandwidth (see the right-hand side axis) and (b) reflectivity-bandwidth product as functions of the atomic vapor density, where the laser is tuned 2 GHz below resonance.

a cw PCM<sup>4</sup> and that the product reaches a maximum value of  $6 \times 10^8$  Hz when  $R_{pc}$  is 670%.

In performing reflectivity measurements, it is important to ensure that the generated beam is the true phase conjugate of the signal beam. Under conditions in which the pump-signal angle  $\theta$  is relatively small ( $\theta \leq \sqrt{\lambda_0/nL}$ ), the generated beam contains additional contributions from forward-four-wave mixing (FFWM), which results in a beam that is not the true conjugate of the signal wave and that therefore cannot be used to perform aberration correction with high fidelity. In this regime, extremely large four-wave-mixing reflectivities can be observed. In recent experiments, reflectivities of 10<sup>5</sup>% (Ref. 16) and 165% (Ref. 17) have been obtained using FWM in AlGaAs diode lasers. However, these devices were operated well within the FFWM regime.

We have taken care to avoid the effects of FFWM by operating with  $\theta \sim 2^\circ - 3^\circ$ . When we operate our PCM in the FFWM regime ( $\theta \leq 1^\circ$ ), we measure reflectivities as high as 2000%.

To summarize, we have demonstrated a phase-conjugate mirror which exhibits a high reflectivity and a fast time response. These characteristics demonstrate that atomic-vapor-based PCMs can be suitable candidates for developing high-gain, high-speed devices for applications in optical signal processing and optical communications.

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