Narrow-band optical filter through phase conjugation by nondegenerate four-wave mixing in sodium vapor

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An ultrahigh-Q, tunable optical filter with a FWHM bandwidth of 41 MHz is demonstrated. The filtering is produced by nondegenerate phase conjugation through four-wave mixing in atomic-sodium vapor. The filter is observed to have a maximum quantum efficiency of 4×10^{-3}. However, degenerate phase-conjugation experiments in sodium suggest that a quantum efficiency of greater than unity can be attained on a cw basis.

The frequency response of phase conjugation through nondegenerate four-wave mixing has been analyzed by several authors[1–5] and has been shown to be capable of yielding a narrow-bandpass optical filter. The filter bandpass is a function of both phase-mismatch constraints and the frequency dependence of the coefficients coupling the waves in the nonlinear process. Optical filtering was recently demonstrated in CS_2, a transparent medium, by using high-power pulsed lasers to provide the pump waves needed in the nonlinear process.[6] The filtering is dependent only on the phase-mismatch constraints in this type of medium. In this Letter we report the first known experimental demonstration of optical filtering by phase conjugation in a resonant system. A resonant system, sodium in this case, has the advantage of providing much larger nonlinear coupling constants than a transparent medium, enabling one to use low-power cw lasers to provide the pump waves. The frequency dependence of the coupling coefficients can result in a filter response that is much narrower than in a transparent medium. An ultrahigh-Q filter with a FWHM bandwidth of 41 MHz is demonstrated in our experiments.

In this experiment, a phase-conjugate signal is generated by the coupling of two counterpropagating pump waves to a signal wave by an intensity-dependent modulation of the atomic population. Physically, the signal wave and one of the pump waves form an absorption grating that diffracts the second pump wave to create the phase-conjugate wave. The output of a passively stabilized Spectra-Physics cw ring dye laser is circularly polarized to provide optical isolation from the laser and is then retroreflected by a mirror to provide the counterpropagating pump waves. An actively stabilized Coherent Radiation cw ring dye laser generates the signal wave, which intersects the pump wave at an angle of 0.39°. Sodium vapor acts as the nonlinear medium. A 2.44-cm-long cylindrical quartz cell of 2.2-cm diameter contains sodium metal in a side arm. The cell is heated to provide the sodium vapor. Cesium metal is also present in the cell and provides a background pressure of 10^{-2} Torr of cesium vapor. The cesium resonances are far from the sodium transition used and do not affect the nonlinear process. The signal wave is chopped mechanically, and the phase-conjugate signal is detected by a P–I–N photodiode that is connected to a lock-in amplifier to provide an excellent signal-to-noise ratio. Figure 1 shows the experimental setup. The pump beam has a FWHM diameter of 0.106 cm and a maximum power of 35.2 mW at the entrance to the cell. The signal beam has a FWHM diameter of 0.15 cm and provides 0.3 mW of power.

Figure 2 shows the frequency dependence of degenerate phase conjugation in sodium when both pump and signal waves are provided by one laser tuned to the $3S_{1/2}$–$3P_{3/2}$ transition at 5890 Å. The pump power is 35.2 mW. The large set of peaks on the left corresponds to the laser tuning through the $F = 2$ hyperfine line of the sodium ground state, whereas the smaller peaks are due to tuning through the $F = 1$ hyperfine level of the ground state. In the nondegenerate case, the pump laser is tuned to the stronger peak of the $3S_{1/2}$ ($F = 2$) to $3P_{3/2}$ ($F = 3$) transition shown in Fig. 2. The temperature of the sodium cell is adjusted to provide a saturated pump-wave transmission of 46% through the cell. This corresponds to a sodium density of $5 \times 10^{11}/\mathrm{cm}^2$. The pump power is 31.5 mW. The signal laser is then scanned in frequency through the transition at 5890 Å, and the measured phase-conjugate signal is shown in Fig. 3. The observed signal has a FWHM bandwidth of 48 MHz and a peak reflectivity of 4×10^{-3}.

An independent photomixing experiment demonstrates that the peak of the signal occurs when the pump and signal lasers are degenerate. When the pump laser is tuned to each of the other three peaks in Fig. 2 and the

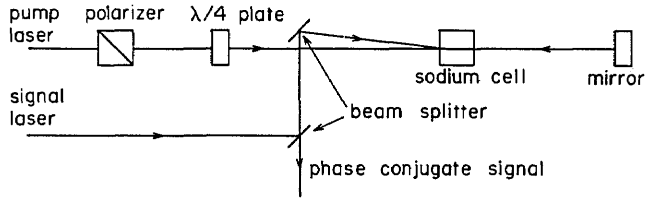

Fig. 1. Experimental setup for cw nondegenerate phase conjugation.

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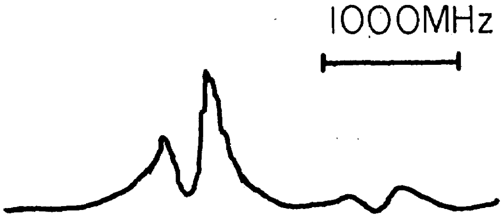

Fig. 2. Reflectivity for degenerate phase conjugation versus laser tuning for the $3S_{1/2}$–$3P_{3/2}$ transition. The laser intensity for the pump wave is 2800 mW/cm^2.

Fig. 3. Reflectivity for nondegenerate phase conjugation versus signal laser tuning with the pump laser fixed on the stronger peak of the $3S_{1/2}$ ($F = 2$) to $3P_{3/2}$ ($F = 3$) transition. The laser intensity for the pump wave is 2500 mW/cm^2.

signal laser is scanned, we observe a similar frequency response, but the reflectivities are smaller.

In Fig. 4, the frequency dependence of degenerate phase conjugation is shown with the pump power attenuated to 2.4 mW. The angle between the signal and pump waves is now 0.32°. There is now one peak when the laser is tuned through the $F = 2$ hyperfine line. This single peak narrows even more as the pump is reduced, with its bandwidth limited by the natural linewidth of sodium.[7,8] The pump laser is now tuned to the peak of the $3S_{1/2}$ ($F = 2$) to $3P_{3/2}$ ($F = 3$) transition shown in Fig. 4. The sodium density is adjusted to provide a saturated pump-wave transmission of 48% through the cell, which corresponds to a sodium density of 1×10^{11}/cm^2. The pump power is 2.5 mW. The signal laser is frequency scanned, and the resulting phase-conjugate signal is shown in Fig. 5. The FWHM bandwidth is measured to be 41 MHz with a peak reflectivity of 6×10^{-5}. The bandwidth remains basically unchanged at the lower pump power, but the reflectivity is greatly reduced.

We have demonstrated an optical filter with a minimum FWHM bandwidth of 41 MHz. From phase-mismatch constraints alone, one can calculate a FWHM bandwidth of 5.2 GHz.[3] The frequency response of a resonant two-level system is limited by the T_2 transverse relaxation time.[1,2,4,5] If we assume that $T_2 = 2T_1$ (T_1 is the natural lifetime, 16 nsec for sodium), then the theory for a Doppler-broadened two-level system yields a FWHM bandwidth of 13 MHz at low intensities.[2] In our system, the frequency jitter of the two dye lasers appears to limit our bandwidth to 40 MHz. It is important to note that we do not observe any significant change in the filter bandwidth as the pump power is increased. Also, the Rabi sidebands, which are theoretically predicted,[5] are not observed. The maximum pump intensity used in these experiments is already 2 orders of magnitude greater than the saturation intensity of sodium. This suggests that much higher pump powers can be used without seriously affecting the filter bandwidth. A maximum reflectivity of 4×10^{-3} is observed for the filter. However, recent degenerate phase-conjugation experiments in sodium vapor have demonstrated amplified reflectivity exceeding unity by using a cw dye laser with a maximum power of 1 W.[9] This suggests that a highly efficient narrow-bandwidth filter can be constructed by using a resonant medium such as sodium. In sodium, it should be noted that hyperfine optical pumping transfers the population of the ground-state hyperfine level resonant with the laser into the other ground-state hyperfine level, thereby diminishing the efficiency of the phase-conjugation process. Resonant systems that do not suffer from this effect, such as an atomic system with zero nuclear spin, should be more efficient and should allow much lower cw pump powers to be used. One disadvantage of the Doppler-broadened system is the narrow field of view of the filter. The maximum phase-conjugate signal is observed in a collinear geometry. The acceptance angle (angle between the signal and pump waves such that the reflectivity is reduced by one half from the collinear geometry) of the filter is approximately the ratio of the natural linewidth to the Doppler width.[2]

The central frequency of the filter can be selected to coincide with that of the hyperfine transitions. The splitting between the two components of the $F = 2$ hy-

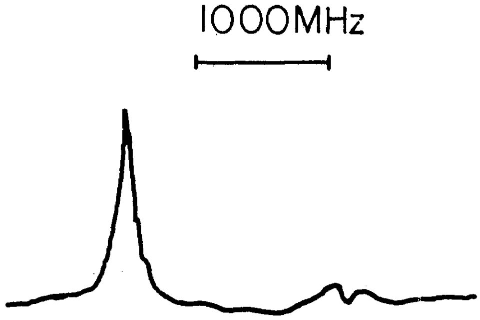

Fig. 4. Reflectivity for degenerate phase conjugation versus laser tuning for the $3S_{1/2}$–$3P_{3/2}$ transition. The laser intensity for the pump wave is 190 mW/cm^2.

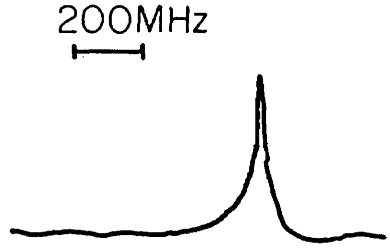

Fig. 5. Reflectivity for nondegenerate phase conjugation versus signal laser tuning with the pump laser fixed on the $3S_{1/2}$ ($F = 2$) to $3P_{3/2}$ ($F = 3$) transition. The laser intensity for the pump wave is 200 mW/cm^2.

perfine transition in Fig. 2 is intensity dependent and increases as the square root of the pump wave intensity in our experiments, indicating that the splitting is probably due to an ac Stark effect.[10] The filter therefore has a limited tuning range that is a function of pump intensity. Additional tuning could be achieved by detuning the pump laser from the atomic resonance as the filter's frequency bandpass is centered at the frequency of the pump wave. This would be at the expense of the phase-conjugate efficiency,[1,2] however.

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