

Sub-Doppler bandwidth atomic optical filter

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We demonstrate what is to our knowledge the first atomic optical filter that uses velocity selection to achieve a passband width that is less than the Doppler width of the filtering transition. A narrow-linewidth pump laser is used to induce circular birefringence in a narrow velocity class of atoms in a dense potassium vapor for 694-nm light resonant with the $4P_{3/2}$ - $6S_{1/2}$ transition. The filter displays a single 170-MHz passband at a peak transmittance of 9.5%. The bandwidth is an order of magnitude lower than that of previously demonstrated atomic optical filters. © 2002 Optical Society of America

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Atomic optical filters transmit light only in a narrow band about a spectral line. They exhibit high peak transmittance, excellent out-of-band rejection, and absolute frequency stability and have been used in free-space laser communication,¹ remote sensing,² and solar magnetometry.³

Atomic filters that exploit resonant enhancement of the circular birefringence of atomic vapor in a magnetic field were demonstrated by Öhman⁴ and later applied to heliospheric magnetometry and velocimetry.⁵ The identical Faraday anomalous-dispersion optical filter (FADOF) was subsequently described in the optical literature for Cs,⁶ Rb, Na, Ca, and K ground-state transitions⁷ and excited-state FADOFs (ESFADOFs) by means of laser pumping in K (Ref. 8) and Rb.⁹

Gayen *et al.*¹⁰ described an excited-state filter based on optically induced birefringence and dichroism without a magnetic field. Their induced-dichroism excited atomic line (IDEAL) filter operated on the K $4P_{1/2}$ - $8S_{1/2}$ (532.3-nm) transition. A circularly polarized laser pump pulse resonant with the $4S_{1/2}$ - $4P_{1/2}$ ground-state transition oriented atoms in the $4P_{1/2}$ state and induced circular birefringence for light that was resonant with the excited-state transition.

In a ground-state FADOF any velocity class of atoms in the vapor may interact with the probe light, so the bandwidth is Doppler limited. In an excited-state filter a narrow-linewidth pump beam will excite only a narrow velocity class of atoms, potentially allowing for sub-Doppler bandwidths. The magnetic fields required for practical ESFADOFs cause Zeeman broadening of the filter passband beyond the Doppler width. The IDEAL filter of Gayen *et al.* did not achieve velocity-selective narrowing owing to the broad pump laser linewidth of 3 GHz, which was much greater than the Doppler width of 875 MHz.

We report an IDEAL filter pumped by a narrow-linewidth cw laser; we observed what to our knowledge was first sub-Doppler passband in an atomic filter. Our filter operated on the K $4P_{3/2}$ - $6S_{1/2}$ transition at 694 nm. We observed a single passband of 170-MHz width, an order of magnitude narrower than previously described filters. This improvement is due to velocity

selection, an effect whose use had not previously been exploited for an atomic filter.

A schematic of the apparatus is shown in Fig. 1. Pump light at 766.701 nm *in vacuo*, resonant with the $4S_{1/2}$ - $4P_{3/2}$ transition, was produced by a cw Ti:sapphire laser (Coherent Model 899) of nominal 500-kHz linewidth. The pump beam was expanded to a 2-mm e^{-2} radius, attenuated, and circularly polarized before it entered the 75-mm K-vapor cell. Probe light at 694.072 nm, provided by a dye laser (Spectra-Physics 380D, Pyridine 2) of 2-MHz linewidth, was attenuated to 10 μ W and linearly polarized. The counterpropagating probe beam was gently focused to ensure that it overlapped the expanded pump beam throughout the cell. The probe beam then passed through a crossed analyzer and was detected by a photodiode. Transmission through the crossed polarizers was less than 10^{-4} with the pump beam blocked and the probe out of band but potentially could be reduced below 10^{-7} with improved optics. The probe beam was chopped and the transmitted photodiode signal synchronously detected to eliminate signal from stray reflections and fluorescence of the pump beam. In a practical device, a dichroic mirror could be used to superimpose the pump and probe beams while preventing pump light from reaching the detector. An oscilloscope synchronized to the dye-laser frequency scan recorded the output of a lock-in amplifier. An etalon signal (free spectral range, 500 MHz) was simultaneously recorded as a frequency marker after having been calibrated against the 462-MHz hyperfine splitting of the ground state

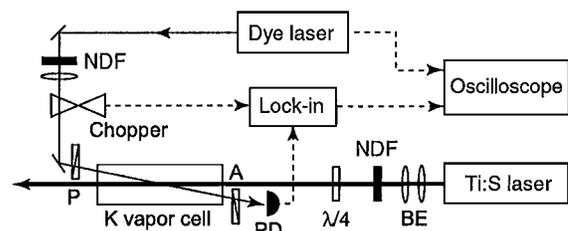


Fig. 1. Schematic of the apparatus: A, analyzer; BE, beam expander; NDFs, neutral-density filters; P, polarizer; PD, photodiode; $\lambda/4$, quarter-wave retarder.

measured by saturated absorption. We calibrated the transmittance by uncrossing the polarizers and measuring the transmitted intensity with the probe beam far from resonance and so unaffected by Fresnel and other optical losses.

The operation of the filter may be understood in terms of an optical pumping model.¹¹ The pumping transition has a saturation intensity $I_{\text{sat}} = 1.8 \text{ mW cm}^{-2}$. At the densities required for practical filter operation, the cell is opaque to pump light at the saturation intensity. It is necessary to use pump intensities much higher than I_{sat} to saturate the absorption sufficiently such that the full length of the cell is pumped. The magnetic hyperfine structure of the relevant K states is shown in Fig. 2 (inset). The σ^+ pump beam tends to transfer the population toward the highly oriented $F' = 3$, $m_{F'} = +3$ state. The population distribution between the excited sub-states after one photon has been absorbed is shown pictorially. After many photons have been scattered, the atom either is in the cycling transition $F = 2$, $m_F = +2 \leftrightarrow F' = 3$, $m_{F'} = +3$, or has been lost to the $F = 1$ ground state. Linearly polarized light incident upon the cell can be considered a superposition of equal parts of σ^+ and σ^- light. If the light is far from resonant with the $4P_{3/2} - 6S_{1/2}$ (694-nm) transition, the vapor neither absorbs nor retards either component, and the unchanged polarization is blocked by the crossed analyzer. For resonant light the σ^+ component is not absorbed or retarded, as selection rules for electric-dipole transitions forbid that. The σ^- component interacts with the vapor and is absorbed and retarded. The result is circular birefringence and partial transmission by the analyzer.

Figure 2 shows a transmittance spectrum of the filter. The transmittance profile is Lorentzian and depends on vapor density (and therefore on temperature), pump intensity, pump detuning, cell length, and the oscillator strength of the filter transition, in our case $f = 0.014 \pm 0.0025$.¹²

Spectra were taken with the pump laser tuned to the center of the Doppler-broadened absorption profile. Detuning the pump laser changes the Doppler shift of the excited atoms and therefore changes the center frequency of the transmittance peak. Hence the filter center frequency may be tuned over approximately one Doppler width.

Transmittance was negligible at temperatures below 80 °C. From 80 to 110 °C, transmittance increased in proportion to the vapor density. Peak transmittance varied little over the range 110–120 °C, but above this range the vapor became optically thick to pump light at the test intensity, and the transmittance decreased. The filter bandwidth was unchanged over 80–150 °C. Such insensitivity to temperature variation is a desirable characteristic in a practical filter. The lack of broadening is noteworthy, as thermalization of the velocity-selected excited-state population should be virtually complete above 130 °C.¹³ In our case of a dilute atomic vapor without buffer gas, thermalization is a result of radiation trapping and resonance exchange, which do not preserve orientation.¹⁴ Hence, orientation is not thermalized and the

filter is robust against this broadening mechanism. Experiments were carried out at 110 °C, corresponding to a density of 10^{12} cm^{-3} .¹⁵

The variation of filter width with pump intensity is shown in Fig. 3. We expect the filter width to be proportional to the width of the velocity class of excited-state atoms and therefore to the power-broadened pump linewidth. Here the pump intensity is well above saturation, and linewidth increases as the square root of the intensity. The data agree well with a square-root exponent.

A figure of merit for bandpass filters is the equivalent-noise bandwidth (ENBW), the width of a rectangular filter with the same peak transmittance that would pass the same amount of broadband noise. Ground-state FADOFs have multiple passbands, yielding ENBWs of 3 GHz. The ENBW of the pulsed K ESFADOF was 8 GHz,⁸ and that of the pulsed IDEAL was 2 GHz.¹⁰ The effective ENBW of our filter is 295 MHz, with a peak transmittance of 10.5% ($I_{\text{pump}} = 500 \text{ mW cm}^{-2}$), and may be reduced to 130 MHz at the expense of a concomitant reduction in peak transmittance to 1.6%.

Figure 3 also shows the variation of peak transmittance with pump intensity I . The transmittance increases as $I^{1.8}$ below a threshold of 150 mW cm^{-2} , above which the increase is $I^{0.25}$. The threshold occurs near the intensity at which saturation causes the

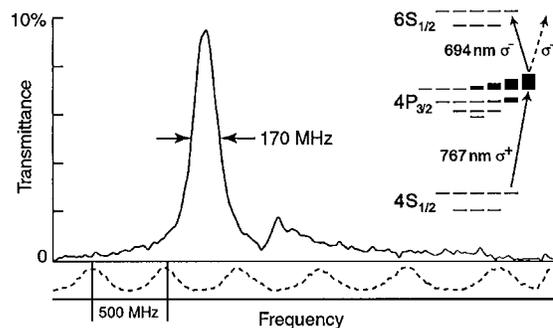


Fig. 2. Transmittance spectrum at 694 nm when $I_{\text{pump}}(\lambda = 767 \text{ nm}) = 330 \text{ mW cm}^{-2}$ and $T = 110^\circ\text{C}$. Dashed curve, an etalon frequency marker. Inset, magnetic hyperfine structure of relevant K levels and relative excited-state occupancies after the first pump photon is absorbed.

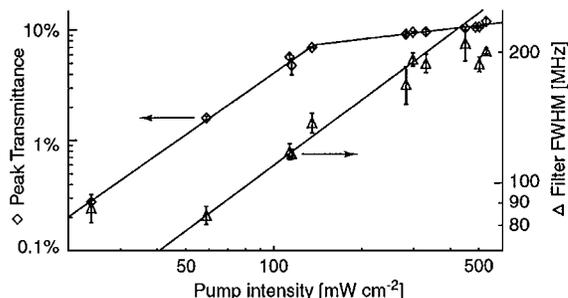


Fig. 3. Transmittance and width characteristics of the filter as a function of pump intensity. The power-law regressions to the transmittance behavior are discussed in the text. The filter width is shown compared with the $I^{0.5}$ behavior expected for pump power broadening.

cell to become optically thin to the pump laser. Increasing the intensity should not significantly increase excited-state occupancy, as the pump transition is well saturated. However, the density of excited atoms should increase in proportion to the power-broadened linewidth (i.e., $I^{0.5}$), and, below threshold, the effective length of the cell should increase in proportion to I . Hence, the column density should scale as $I^{1.5}$ below and $I^{0.5}$ above threshold. Deviation from this simple model at high I may result from competing nonoriented pumping as a result of radiation trapping.

Only one of the reported ESFADOFs had a peak transmittance above 10%,⁹ and this was due to the relevant oscillator strength, which was more than twice that of the transition that we investigated. Gayen's IDEAL filter achieved a peak transmittance of 40% on a weaker transition but used pulsed pumping to excite more than 50% of atoms and exhibited a much wider bandwidth than did our filter.

In a separate experiment, an electro-optic modulator was used on the pump beam to provide a repumping sideband and suppress trapping into the $F = 1$ ground state. Whereas the peak transmittance was thus marginally increased, a significant and undesirable second peak occurred in the transmittance spectrum as a result of the inclusion of a second velocity class of atoms that corresponds to the excitation of the $F = 1$ ground state. A similar filter that employs rubidium or cesium, for which the ground-state hyperfine splitting is greater than the Doppler width, would not display the second peak and hence would be expected to benefit from repumping.

Ground-state atomic filters are noted for their wide fields of view, which in our filter are limited only by the transverse area of the vapor cell that may be excited with the available pump power. The passband will be wider for rays at extremal angles owing to residual Doppler broadening.

Energy pooling¹⁶ places an upper limit on the vapor density in this filter, as it converts pump light at 767 nm into fluorescence near 694 nm, which is detected as noise. Upper states are populated by the collision $4P_{3/2} + 4P_{3/2} \rightarrow 4S + 6S, 5P, 4D + \Delta E$. The $5P$ product has the greatest rate coefficient but produces only violet and infrared fluorescence, which could be rejected with an additional interference filter. Whereas most atoms excited to the $6S_{1/2}$ state decay by means of the $6S \rightarrow 5P \rightarrow (5S \rightarrow 4P \rightarrow)4S$ violet-infrared cascade, 5% of them decay directly to the $4P$ state, emitting at 694 nm.

The energy pooling rate is proportional to the square of the density of atoms in the $4P_{3/2}$ state and hence is a strong function of temperature. At 190 °C this noise source was clearly visible as violet fluorescence. We estimate isotropic noise emission of 10^6 – 10^7 photons $\text{cm}^{-3} \text{s}^{-1}$ at 110 °C and $I = 50I_{\text{sat}}$. Filters based on excited-state transitions with wavelengths well removed from the pump wavelength will generally not be so constrained.

Increasing the column density of oriented excited-state atoms should increase the transmittance. In-

creased density is expected to increase energy-pooling and thermalization effects, whereas increased cell length is not. We predict greater peak transmittances if the path length through the cell is increased, either by use of a longer cell or by passage of the probe beam through the cell multiple times.

There are many other excited-state transitions with oscillator strengths greater than 0.005 for which velocity-selective IDEAL filters might be implemented. The 694-nm transition was chosen for its moderate oscillator strength and convenient wavelength and is excellent for diode-laser free-space communication. Communications wavelengths of 1323, 1366, and 1529 nm may also be reached with Rb filters.

We have shown that velocity selection may be applied to atomic filters. The velocity-selective effect is robust against thermalization at the high vapor densities required for a practical filter. Filter bandwidth is reduced below the Doppler width for what we believe is the first time, while the stability, image preservation, rapid response time, and high transmittance of traditional atomic filters are retained.

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