Polarization Independent Atomic Prism filter for removing Amplified Spontaneous Emission

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We create an optical frequency, polarization independent, narrow band-pass filter of 1.3 GHz (3 dB bandwidth), using the steep dispersion near the Rubidium D1 atomic transitions within a prism-shaped vapor cell. This enables us to clean the amplified spontaneous emission from a laser by more than 3 orders of magnitude. Such a filter could find uses in fields such as quantum information processing and Raman spectroscopy.

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1. INTRODUCTION

A laser amplifies stimulated emission using a gain medium and a cavity. However when the gain media is broadband one inevitable side effect will be the amplification of spontaneous emission, (ASE) [1]. This ASE appears as a low power broadband pedestal to the relatively high power narrow bandwidth lasing signal, all in the same spatial mode. The precise amount of ASE will depend on the gain media, cavity and operating conditions of the laser. For some applications, the ASE is a desirable source of incoherent light in a well defined spatial mode [2], while for most applications this ASE will appear as a small amount of noise.

However, there are experiments, such as in Raman spectroscopy and in quantum information processing, where this background (typically rated at $< -30$ dB) can still significantly affect the SNR and special methods must be employed to reduce it further. For example, consider a situation like the DLCZ protocol where a control pulse produces a quantum signal [3, 4], in a very close spatial and frequency mode which must be filtered. In situations like these even with 60dB suppression of ASE there will be 1pW of ASE for every mW of laser, producing $O(10^6)$ photons every ms, which can be a very large background if your signal is one photon! For these highly sensitive applications two main technologies are used to increase SNR, specialized Bragg gratings [5, 6], and Fabry-Perot etalons [7]. Specialized gratings can reach a transmission width of around 50 GHz, whereas etalons can have widths of 100 MHz, but with less suppression [8].

In this paper we take one of the most well known optical elements, a prism [9], and replace the glass with a relatively dense $10^{14}$ cm$^{-3}$ atomic vapor. At frequencies close to atomic transitions a large change in refractive index occurs $O(0.001)$ over a very small frequency $O(\text{GHz})$ producing a dispersive power many orders of magnitude larger than glass. With this effect we separate laser light from ASE even up to few hundred MHz. In Section 2 we outline the basic theory, then in Sections 3 & 4 we describe our preliminary implementation, followed by a discussion in Section 5 and concluding remarks in Section 6.

2. THEORY

The refractive index of an atomic ensemble is directly related to the susceptibility, (see Eq. 1). This susceptibility is modeled by the convolution of the Lorentzian atomic transitions with the Doppler broadening, known as the Voigt profile, together with a
way to increase the sensitivity is to work at higher temperatures (greater than 150°C) has been demonstrated to create a vapor with a dispersive power many orders of magnitude larger than standard materials [12,13].

\[
\eta = s/\sigma(L) = \frac{L\delta(\omega)}{\sigma\sqrt{(1-\frac{f}{L})^2 + \left(\frac{L}{f\sigma}\right)^2}}. \tag{4}
\]

This will have a maximum at \( L = f \)

\[
\eta_{\text{max}} = \frac{\delta(\omega)z_R}{\sigma_0} = \frac{\delta(\omega)\pi c_0}{2\lambda_0}. \tag{5}
\]

Interestingly we see that the maximum sensitivity is at the focal length and not at the slightly closer position of the new beam waist. Also we see that for a fixed prism angle, the only way to increase the sensitivity is to work at higher temperatures (greater \( \delta(\omega) \)) or a larger beam diameter.

3. METHOD

To practically demonstrate this effect, we work with the alkali metal Rubidium in a natural abundance vapor cell at the D1 transitions (795 nm). For the prism, we use a cylindrical cell (diameter=2.54 cm) cell with angled faces (45°). To obtain sufficient atomic density, we heat the cell by placing it in an aluminum box and wrapping the bow with about 14 winds of Nikrothal 60. We then apply up to 54 W of power to heat the device to around 150°C. Entry and exit openings for the laser are left in the box, as well as for a "cold" spot at a distance of a few centimeters from the prism regime [15]. This creates a location for a point of condensation away from the prism when the Rubidium cools, and where we measure the temperature of the cell (using a Thorlabs TH10K thermistor). We work with two TOPTICA lasers. The first is a DFB, with which we work with non-standard parameters (current slightly above lasing threshold) to increase the ASE ratio (from \( \sim 30 \text{ dB} \) to \( \sim 10 \text{ dB} \)), without doing this we would not have sufficient dynamic range in our equipment for the measurements. The second laser is a DLPro (with an ASE ratio of \( \sim 60 \text{ dB} \)), which effectively acts as an ASE free source (for our sensitivity). The laser enters through the curved side of the cell, and exits through the flat angled face. To compensate for the lensing effect of the curved cell wall, we place a cylindrical lens before the prism. The laser light is coupled into a single mode fiber. After exiting the fiber we collimate the light (diameter = 2.1mm) before it passes through a cylindrical lens upon entering the prism. After exiting the light is focused. An imaging lens in conjunction with a mirror on a flipper enables us to image this plane onto a camera (Point Grey Firefly MV) or to observe the signal in a spectrometer (Ocean Optics HR2000+) or photodiode (Thorlabs PDA36A), see Fig. 1.

4. RESULTS

First, we demonstrate the ability of the prism to cause a frequency-dependent deflection. This deflection is observed to be independent (to within 5%) upon rotation of a \( \lambda/2 \) waveplate. Polarization independence is entirely consistent with the theory, Sec. 2, which, due to the relatively large detuning and lack of magnetic fields, is insensitive to the subtleties of the Rubidium hyperfine structure. The inset in Fig. 1 shows the laser light being separated from the ASE by approximately 8e. Despite the inherent 10dB suppression of the ASE, when all frequencies are considered there is more power in the ASE than at the lasing frequency (because we are operating with the DFB laser just above threshold). The small shift in the vertical direction arises from our optical set-up using a curved cell wall. As we heat the prism small movements occur which misalign our compensa-
the ASE is deflected by $\Gamma$ while the amplitude is $I_\text{sat}$, Eq. 3, and the transmitted intensity there will be optical pumping that effectively reduces the atomic density, the large detuning means that there is corresponding reduction in the scattering rate.

$$R = \frac{I}{I_\text{sat}} \cdot \frac{1}{1 + 4(\Delta/\Gamma)^2 + (I/I_\text{sat})},$$

where $\Gamma$ is the spontaneous emission rate, $I$ is the laser intensity, $\Delta$ is the detuning, and $I_\text{sat}$ is the saturation intensity. A simple model considering the transit time of an atom transversing the beam shows that for our experimental parameters we could use 200 mW of power without a significant (<5%) change in deflection.

Next we place a 100 $\mu$m diameter pinhole at the location of the laser light in the focal plane, transmitting the laser and blocking the ASE. The transmission efficiency is <40%, (this is not intrinsic but related to mismatching between the pinhole and the beam shape). Increasing the pinhole radius will transmit the atomic density, the large detuning means that there is corresponding reduction in the scattering rate.

$$T_\text{ASE} = \int_{y'-a}^{y'+a} \int_{x'-a}^{x'+a} I_\text{ASE} e^{-2(x'^2+y'^2)/\omega'^2} dxdy,$$

where $\omega'$ is the new waist of the focused beam, $a$ is the radius of the pinhole and the parameter for the integration over $y$ is $y' = \sqrt{a^2 - (x-s)^2}$. However, in practice real laser beam shapes need to be considered in the transmission/filtering tradeoff, which in our experiment was also influenced by the optics (our curved wall and compensation).

We now compare the spectrum of the light with and without the pinhole, Fig. 3. The red (dotted) line shows the spectrum without any pinhole, that is with ASE, while the black (solid) line shows the spectrum with the pinhole, that is the cleaned laser light. We believe that the spread in the cleaned laser light is a limitation of the spectrometer's point spread function and not from ASE. This is seen on the DLPro laser which is effectively clean from ASE on this scale. The green (dashed) line shows that the DLPro spectrum, after normalization, which essentially follows the background of the cleaned laser light. This places the background at a few counts/sec and an ASE suppression of greater than 30 dB. It is interesting to note the small signal at 780 nm which comes from a small amount of ASE at the frequency of Rb(2P) transitions which is deflected into the pinhole. The focusing lens (L2 in Fig. 1) collects the spontaneous emission from ASE. This is seen on the DLPro laser which is effectively clean from ASE on this scale. The green (dashed) line shows that the DLPro spectrum, after normalization, which essentially follows the background of the cleaned laser light. This places the background at a few counts/sec and an ASE suppression of greater than 30 dB. It is interesting to note the small signal at 780 nm which comes from a small amount of ASE at the frequency of Rb(2P) transitions which is deflected into the pinhole. The focusing lens (L2 in Fig. 1) collects the spontaneous emission from ASE. This is seen on the DLPro laser which is effectively clean from ASE on this scale. The green (dashed) line shows that the DLPro spectrum, after normalization, which essentially follows the background of the cleaned laser light. This places the background at a few counts/sec and an ASE suppression of greater than 30 dB. It is interesting to note the small signal at 780 nm which comes from a small amount of ASE at the frequency of Rb(2P) transitions which is deflected into the pinhole. The focusing lens (L2 in Fig. 1) collects the spontaneous emission from ASE. This is seen on the DLPro laser which is effectively clean from ASE on this scale. The green (dashed) line shows that the DLPro spectrum, after normalization, which essentially follows the background of the cleaned laser light.

Finally, in order to measure the width of our bandpass filter, we replace the spectrometer with a photodiode. We use...
Fig. 4. The main figure shows a logarithmic plot of the pinhole transmission as a function of frequency. The red line shows the transmission without the pinhole, while the black line shows the transmission with the pinhole. The inset shows the non-log plot of the same data.

The clean DLPro laser, scanning the frequency with corresponding spatial shift and measuring the transmission through the pinhole. The results, Fig. 4, clearly demonstrate the narrowness (1.3 GHz, 3 dB) of the filter, with a >30 dB suppression far from the transmission frequency, $v_0$. As expected the filter is asymmetric. We have chosen $v_0$ to be red detuned from the D$_1$ lines, this means that at frequencies greater than $v_0$ there is a rapid falloff due to the resonant absorption of the Rubidium. Even at frequencies greater than the Rubidium D$_1$ lines there is still a shift of the light in the direction away from the pinhole which aids the suppression. When the frequency is decreased from $v_0$ the opposite is true, with the light shifted towards the pinhole and hence causing a slower falloff in the suppression.

5. DISCUSSION

Our preliminary experiments clearly demonstrate the ability of the prism to reduce ASE by 3 orders of magnitude, Fig. 3 & 4 which approaches the limit of the dynamic range of our equipment.

Upon investigation we also found that the suppression was also limited by the laser beam profile. A truly Gaussian beam will have a much sharper fall off in intensity than we observed, see Fig. 5. We should observe the same ASE suppression (30dB) for a shift corresponding to 3-$\sigma$ however we required shift of about 8$\sigma$. This is mainly explained by the spatial mode quality. Even though our spatial mode is a very good approximation to a Gaussian beam, at radial displacements greater than a few $\sigma$ there is a much slower fall-off in the intensity than expected, see the insets in Fig. 5. This limits the effectiveness of the spatial filter, requiring a bigger shift to separate the shifted spatial mode from the original mode.

Even with our non-ideal beam our results compare very favorably to the other options for narrow pass optical filters. Our filter is 50 x narrower than the best ASE filters known to us, [6] while the suppression ratio is hard to compare with the available data. Extremely narrow filters with kHz bandwidth have been made, however these require coherent media such as EIT [17, 18]. High finesse etalons can reach 100’s MHz, but they do not come close in their suppression ratio, especially considering the repetitive nature of their pass band. Our filter, as a forward propagating spatial block also prevents the issues associated with the reflections and distortions of high finesse cavities, especially at higher powers. The prism also allows for many different spatial modes of the light, but where a spatial extension in the direction of the shift will decrease the filter efficiency.

As with almost all Atomic Resonance Filters (ARF) [19, 20], there is an obvious limitation in that we have a very small region of tunability. The prism works most effectively at both the blue and red sides of the Doppler broadened absorption, although by appropriate positioning of the pinhole it may be used at any frequency where there is sufficient deflection for the required application [21]. It should be noted that many applications allow for a compatible frequency to be chosen [22]. Also in the field of quantum information processing, a frequency close to an atomic resonance is desirable [23]. One often has the ability to choose an appropriate isotope for the filter corresponding to the atoms being used material e.g. $^{87}$Rb for filtering a wavelength on the $^{85}$Rb transitions [27]. Other small frequency changes could be accomplished by devices such as an AOM. It should be noted that for a quantum information experiment the small signal at a very far detuned transition (in our experiment the small signal at the Rubidium D$_2$ (780nm) transition...
We have presented a novel method to create a high suppression width, ENBW with other ARFs. It is simple to implement, has a single pass (>30 dB) ultra narrow (1.3 GHz) optical frequency pass filter. We compare competitively with the state of the art for Faraday rotation filters [24]. The potential for very high performance exists across a broad range of atoms and their resonances.

6. CONCLUSION
We have presented a novel method to create a high suppression (>30 dB) ultra narrow (1.3 GHz) optical frequency pass filter. We have demonstrated it to suppress ASE. Theoretically the transmission can approach unity, while the suppression can be many orders of magnitude. Such a filter working near atomic resonances could find useful applications in quantum information processing and other areas.

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16. Our measurement exploits the 2 × 10⁸ system dynamic range. However the PSF appears to be related to the stray light (<0.05%) and individual measurement SNR (250:1) (HR 2000 Specifications). This PSF explanation is consistent with Fig. 4 and the Topica DLPro data sheet.
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