Optical vortex filtering for the detection of Electromagnetically Induced Transparency

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(Dated: June 28, 2011)

We report the realization of an optical filter based on an optical vortex mask designed to exclusively detect a weak coherent laser field in the presence of much stronger spatially-overlapping fields. We demonstrate the performance of such an optical vortex filter to eliminate the strong control field and detect only a weak optical field’s transmission under the conditions of electromagnetically induced transparency. The attractive feature of such filter is its insensitivity to optical field frequencies and polarizations, which makes it applicable for a wide range of coherent processes.

PACS numbers: 070.6110, 270.1670, 120.2440

The problem of detecting a weak optical signal in the presence of other strong laser fields is inherent to many optical experiments. In particular, this problem arises in experiments involving electromagnetically induced transparency (EIT) [1, 2], in which optical properties of a weak probe field can be coherently controlled by means of a strong classical control field. The most common EIT configuration is a three-level Λ system, shown in Fig. 1(a), in which the control and probe fields connect two long-lived hyperfine or Zeeman sublevels of the electronic ground state with a common excited level. In this case, the presence of the control field leads to a strong coupling between the probe field and a collective atomic spin excitation that results in strong suppression of resonant absorption, and opens a narrow window of transparency, \(\Gamma_{\text{EIT}} = \gamma_0 + |\Omega_C|^2/(\sqrt{d\gamma})\), where \(\gamma_0\) is the inverse lifetime of the Zeeman coherence, \(\Omega_C\) is the Rabi frequency associated with the control field, and \(\gamma\) is the optical polarization decay rate. Here, we define the optical depth, \(2d\), such that the probe intensity without EIT is attenuated by \(e^{-2d}\). The accompanying steep normal dispersion allows for dramatic group velocity reduction \(v_g/L \propto |\Omega_C|^2/(d\gamma) \ll c\) (“slow light”), where \(L\) is the length of the medium, and the reversible mapping of a probe pulse onto a long-lived atomic coherence (“stored light”) [2, 3, 6]. These phenomena present promising avenues towards technologies like miniature atomic clocks [4, 5], all-optical delay lines [6], single photon sources [7–9], efficient quantum memories [10, 11], and magnetometers [4, 5], all-optical delay lines [6], single photon sources [7–9], efficient quantum memories [10, 11], etc.

However, the exclusive detection of a weak probe field, especially at the few-photon level, in the presence of a strong control field becomes a challenging experimental task. Since the two optical fields have similar frequencies (differing by a few GHz for a Λ-system based of different hyperfine ground state sublevels to a sub-MHz difference for Zeeman sublevels of the same hyperfine manifold), traditional dichroic or interference filters are not effective, and thus only narrow-band transmission elements (such as high-finesse Fabry-Perot étalons) [8, 12, 13] or high-quality polarizers (for orthogonal control and probe fields) must be placed before a probe detector to suppress the control field. These filtering methods are often very sensitive to frequencies and polarizations of the two optical fields, and impose restrictions on experimental arrangements. Spatial filtering has been successfully implemented in most cold atom experiments; however, experimental realizations of EIT in a warm atom system require nearly collinear propagation of the signal and control fields to avoid large two-photon Doppler broadening of the EIT resonance \((\vec{k}_s - \vec{k}_p) \cdot \vec{v}_{\text{atoms}}\). Thus, an appropriate spatial filter must efficiently discriminate two optical fields propagating at very small angle with respect to each other.

In this paper, we present a proof-of-principle demonstration of an optical vortex filter (OVF) that we used to detect a weak probe laser field in the presence of a strong coherent control field under conditions of EIT. This filtering method is largely insensitive to the polarizations and frequencies of two optical fields and thus lacks the complications associated with spectral and polarization filtering mentioned above. It can also be used in conjunction with other filtering methods, if a single filtering method is not sufficient.

An optical vortex also known as a phase singularity or screw dislocation [14], is a zero of optical field intensity within an otherwise non-zero field. The cross-sectional field amplitude of a beam carrying an optical vortex can be described, in polar coordinates \(r, \theta\), as:

\[
E(r, \theta) \propto \left( \frac{r}{w_0} \right)^m \exp \left[ - \left( \frac{r}{w_0} \right)^2 \right] \exp \left[ im\theta \right],
\]

where \(w_0\) is the beam waist, and \(m\) is the topological charge of the vortex, which characterizes the number of \(2\pi\) phase variations within the vortex.

In principle, an optical vortex beam is created by transmitting a Gaussian laser beam through a transparent phase mask having azimuthally-varying thickness, \(d = d_0 - m\lambda_0(2\pi)\Delta n\), where \(d_0\) is the maximum thickness, \(\lambda_0\) is the specified wavelength, and \(\Delta n\) is the refractive index difference between the mask and its surroundings. The beam acquires a spatial profile with an azimuthal harmonic phase \(\phi = m\theta/(2\pi)\). In the center of the mask, the phase is undefined, and the transmitted beam interferes destructively creating a region of zero intensity. However, due to the manufacturing difficulty of creating a smooth spiral phase of this type, a “spiral stair-
The transmitted (more powerful) beam adheres. The two beams were separated on a polarizing trol fields were derived from the same external cavity with weak classical probe fields, since it does not allow the same circular polarization. The attractive fea-
tions.

The basic idea of an OVF is the following: both over-

In our experiment, we used a prototype OVF to de-

An ideal filter will completely extinguish the control field without affecting the probe field. In reality, however, there are several factors limiting the OVF performance. For example, the vortex mask does not have a continuous thickness, but rather consists of eight steps with sharp boundaries that contribute to diffraction; also, any small manufacturing imperfections in the vortex mask center break conditions for perfect destructive interference and thus increase the amount of light in the dark part of the case" mask is typically manufactured. In our experiment, the phase plate had eight “steps”, such that its thickness as a function of the azimuthal angle \( \theta \) can be described as

\[
d = d_0 - m \lambda_0 \left( \frac{80}{(2\pi)} \right) \Delta n, \]

where \( \lfloor \ldots \rfloor \) indicates usage of the floor function. This phase mask produces the same destructive interference at its center—resulting in a region of zero intensity—but may produce unwanted diffraction, owing to the sharp discontinuities at the step boundaries.

The attractive feature of such polarization arrangement is that it can be accurately approximated by a simplified three-level \( \Lambda \) system \[14\], but so far it has been limited to experiments with weak classical probe fields, since it does not allow polarization filtering.

The experimental setup for evaluation of the OVF performance is shown in Fig. \[a\] (b). Both probe and control fields were derived from the same external cavity diode laser (ECDL) to preserve their mutual phase coherence. The two beams were separated on a polarizing beam splitter. The transmitted (more powerful) beam passed through an acousto-optical modulator (AOM), and the first diffraction order with its frequency shifted by \(-80\) MHz was used as a control field in EIT experiment. The reflected beam was phase-modulated using an electro-optical modulator (EOM) at frequency \(6.7547\ GHz\), which matches the hyperfine splitting of \(87\)Rb ground state levels \((6.8347\ GHz)\) minus \(80\) MHz. The +1 modulation sideband was then filtered using a temperature tuned Fabry-Perot etalon (FPE) and served as a probe field. The other EOM modulation sideband and the main carrier were suppressed by a factor of approximately 1 : 100; moreover, since the modulation frequency differed from the hyperfine splitting, they do not effect probe field propagation through nonlinear mixing.

The control and probe beams were then recombined in a non-polarizing beam splitter cube (NPBS) at a small angle 0.92 mrad and converted into parallel circular polarizations by a quarter-wave plate (\(\lambda/4\)) placed before the cell. Both probe and control beams had similar divergence of approximately 0.38 mrad, so it was virtually impossible to separate them even after long propagation.

The powers of the control and probe fields before entering the Rb cell were correspondingly 1.15 mW and 40 \(\mu\)W, and their respective diameters were 1.52 mm and 0.47 mm. A cylindrical Pyrex cell (length \(L = 7.5\ cm\) and diameter \(2.5\ cm\)) containing isotopically enriched \(87\)Rb and 5 Torr of Ne buffer gas was mounted inside three-layer magnetic shielding to reduce the influence of stray magnetic fields. The temperature of the cell was maintained at 50.0°C, which corresponded to an optical depth of \(2d = 49\). Our procedure for calculating the optical depth is described in Ref. \[10\].

The OVFs have been effectively used to distinguish a dim signal from a stronger background in several applications, such as the detection of extra-solar planets \[15–17\] and incoherent scattering \[18\].
FIG. 2. Left column: Measured profiles of the control field before (a) and after (b) the phase mask. Middle column: Recorded (c) and calculated (d) diffraction pattern of the optical vortex (the control field after the phase mask) through the pinhole. Right column: Recorded (e) and calculated (f) diffraction pattern of the probe field after the phase mask through the pinhole. All images have been inverted in order to exhibit the higher order diffraction fringes.

FIG. 3. (a) Attenuation of the control and probe fields after OVF. (b) An EIT resonance in the probe field, detected after passing through the OVF (black) and without OVF (red). For easy lineshape comparison, the background is subtracted, and the resonance amplitude is normalized to one in both cases.

to exhibit the higher order diffraction fringes. Furthermore, diffraction of the signal field leads to unwanted attenuation, as energy is lost to higher order modes and imperfect matching of the pinhole aperture size to the width of the probe beam.

For our experiments, the observation plane (i.e., the position of PD or camera) was approximately \( z = 15 \text{ cm} \) from the vortex. Thus, the diffraction criteria \( a^2/(\lambda z) \approx 0.10 \ll 1 \), so we are in the Fraunhofer or far-field regime. The far-field diffraction pattern through a circular aperture of radius \( a \) can be computed as follows [21, 22]:

\[
U(\rho, \psi) \propto \int_{0}^{2\pi} \int_{0}^{a} E(r, \theta) e^{-ikr\rho/z \cos(\theta-\psi)} r d\rho d\theta,
\]

where \( \rho \) and \( \psi \) are the corresponding radial and azimuthal variables in the observation plane, placed at a distance \( z \), and \( k = 2\pi/\lambda \) is the wavenumber of light incident on the aperture. Inserting the expression for \( E(r, \theta) \) given by Eq. (11) with \( m = 1 \), we find

\[
U(\rho, \psi) \propto \int_{0}^{2\pi} \int_{0}^{a} \left( \frac{r}{w_0} \right)^{2} e^{-i(\psi-\pi/2)} e^{-ikr\rho/z \cos(\theta-\psi)} r d\rho d\theta.
\]

The angular integral can be computed analytically [22], leaving the radial integral,

\[
U(\rho, \psi) \propto e^{i(\psi-\pi/2)} \int_{0}^{a} \left( \frac{r}{w_0} \right)^{2} e^{-i(\psi-\pi/2)} J_1(kr\rho/z) dr,
\]

which can be evaluated via infinite series [21] or numerically. Here, \( J_1 \) is the first order Bessel function of the first kind. Similar methods can be used to calculate the diffraction pattern formed by a Gaussian probe pulse through the aperture. Figs. 2(d,f) depict the results from numerically integrating the Fraunhofer diffraction integral for both the control and probe fields. Clearly, they are in a good qualitative agreement with experimental observations shown in Figs. 2(c,e). We show the inverted images to make the weaker diffraction fringes more discernible. Such calculations can be used to determine the optimal size of the pinhole that simultaneously yields maximum suppression of the control field and maximum transmission of the probe field. Additionally, the calculations confirm that the probe inefficiency is due in large part to a non-optimal aperture size.

Finally, Fig. 3(b) shows the measured probe EIT resonance recorded with and without OV filtering (black and red curves, respectively). Although OV filtering does reduce the signal power due to a non-optimal pinhole size, the method clearly preserves the overall EIT lineshape. The small discrepancy between the EIT resonance width is caused by the clipping of the wings of the intensity distribution of the probe field. In this case, we effectively detect only the part of the beam with highest and most uniform control field intensity, which results in a more symmetric power-broadened resonance.
filtering, the regions with lower intensity (hence smaller power broadening) also contribute resulting in a overall slightly narrower resonance with sharper top [22].

In conclusion, we demonstrated the possibility of using an optical vortex filter to detect a weak coherent probe field in the presence of a much stronger control field under conditions of electromagnetically induced transparency. The best demonstrated control field suppression factor is better than $10^{-4}$. The main limitation of the proposed method—due to the diffraction though the pinhole—can potentially be improved by carefully selecting the pinhole size. Filtering improvement can be made by using a phase mask with higher topological order [13]. The proposed method may be beneficial for a wide range of optical experiments due to its several advantages, such as weak sensitivity to the optical fields’ polarization and frequency, as well as only a weak distortion of the probe field wavefront.

The authors thank Kelly A. Klutts and Carlos Lopez-Mariscal for useful discussions, and G. A. Swartzlander for valuable advice and for loan of one of his phase masks. This research was supported by NSF grant PHY-0758010, and by the College of William and Mary through the summer REU program.

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