Compact phase delay technique for increasing the amplitude of coherent population trapping resonances in open Λ systems

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We propose and demonstrate a novel technique for increasing the amplitude of coherent population trapping (CPT) resonances in open Λ systems. The technique requires no complex modifications to the conventional CPT setup and is compatible with standard microfabrication processes. The improvement in the CPT resonance amplitude as a function of intensity of the excitation light agrees well with the theory based on ideal open and closed Λ systems.

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Recently the physics of coherent population trapping[1–4] (CPT) has received increased attention, in part because of applications of the phenomenon in miniature atomic devices such as atomic clocks.[5–7] In particular, the amplitude of the CPT resonance is of high importance in determining the performance of such devices. It was pointed out that in some multilevel atomic systems population loss to levels not excited by the laser light would lead to reduced contrast and inferior performance.[8,9] Techniques to overcome this drawback and improve the CPT resonance amplitude have been developed[10–12] but have not retained the original simplicity of the conventional CPT setup. Here we propose a novel technique in which light from two closely spaced vertical cavity surface emitting lasers (VCSELs) is used to significantly boost the amplitude of a CPT resonance excited in a microfabricated alkali vapor cell.[13] A VCSEL die is typically under 100 μm in size, consumes very little power, and can be mass produced, all of which enhance the technical feasibility of the scheme.

For atomic clock applications, the $|m_f=0\rangle$ ground states excited with circularly polarized light resonant with the $D1$ line of ^{133}Cs and ^{87}Rb atoms [see Fig. 1(a)] have proved very valuable.[14]

The circularly polarized light fields (say σ^+), however, tend to optically pump a large fraction of the atoms into another incoherent dark state, $|F,m_f=F\rangle$, which is not coupled to any of the excited states by the incident light fields. The atoms trapped in this state do not contribute to the CPT resonance, which reduces the strength of the detected signal.[8]

A simple technique for improving the CPT resonance signal therefore is to depopulate the incoherent trapping state without affecting the atoms already contributing to the signal. This can be achieved by exciting two separate Λ systems on the $|m_f=0\rangle$ ground states, as shown in Fig. 1(b), by using a combination of σ^+ and σ^- polarized light fields. The presence of both polarizations ensures that the trapping state $|F,m_f=F\rangle$ is eliminated, allowing a majority of atoms to contribute to the CPT resonance signal. However, this cannot be accomplished simply by using a linearly polarized light field propagating along the quantization axis because the dipole selection rules prevent a CPT resonance from being excited.[15,16]

Recent proposals to overcome this difficulty[10,11] differ in details, but are based on a common approach. The basic idea is to introduce a time delay between the σ^+ and σ^- components of the linearly polarized light fields. By delaying either component of the light field (σ^+ or σ^-) in time by $t=\pi/\Delta\omega_{12}$ through a difference in optical path length, the dark states associated with them can be aligned, which allows the two CPT resonances to constructively interfere. The drawback here, however, is that, besides requiring complex modifications to the setup for splitting and recombining the two components of the light fields, the required path difference of $\sim$2 cm for alkali at-

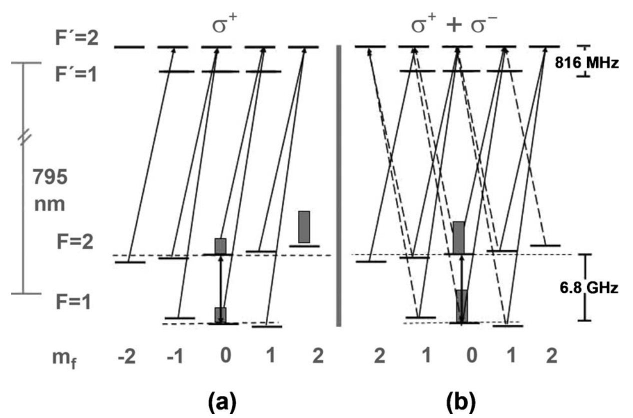

Fig. 1. (a) σ^+ polarized light fields incident on the $D1$ line of ^{87}Rb in Λ configuration. A large fraction of atoms is lost to the $|F=2,m_f=2\rangle$ state, resulting in a loss of CPT resonance signal. (b) A combination of σ^+ and σ^- light fields can be used to accumulate a maximum number of atoms in the CPT dark state on $m_f=0:0$ ground states.

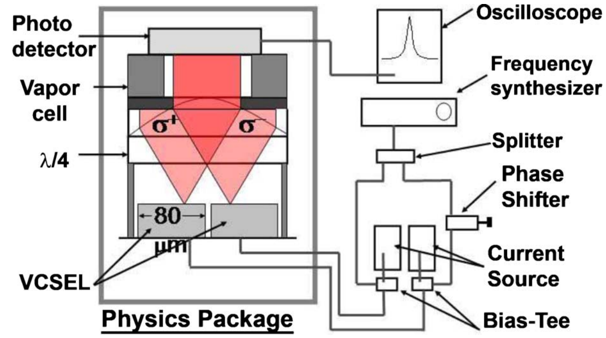

Fig. 2. (Color online) Schematic of the experimental setup. The proposed technique is experimentally implemented in a highly miniature physics package.

oms makes it impractical to implement this technique in devices that are projected to have dimensions of less than a few millimeters.

To overcome these drawbacks, we demonstrate the following simple alternative. To produce a combination of σ^+ and σ^- light fields with an appropriate time delay, light from two independent VCSELs with appropriate polarizations is directly used. This considerably reduces the complexity of the physics package, as no additional optics are required. While some additional electronic systems are needed, these can be implemented in small size and low power with microprocessor-based electronics. The time delay required between the two sets of light fields can then be introduced by simply delaying the phase of the microwave modulation on one of the VCSELs by π.[17] Since this delay can be easily implemented by using miniature electronic components, this technique places almost no additional constraints on the size of the device.

Some other alternative schemes have been recently proposed to increase the CPT resonance amplitude by depopulating the incoherent trapping state. Taichenachev *et al.*[18] excited a CPT resonance on the $m_f=+1:-1$ Zeeman ground states instead of $m_f=0:0$ ground states by using a single linearly polarized laser. Despite its simplicity, this technique is projected to work only in vapor cells with low buffer gas pressures for which the excited state hyperfine manifold on the $D1$ line of Rb atoms is well resolved. This therefore limits the implementation of this technique in miniature vapor cells, which require considerably higher buffer gas pressures to suppress the wall-collision-induced ground state decoherence. In a technique proposed by Zanon *et al.*,[12] a CPT resonance was excited on the $m_f=0:0$ ground states by using two phase-locked lasers with perpendicular linear polarizations. In this technique the coherence between the lasers was required because each Λ system used one field component from each laser. The additional complications in using phase-locked lasers again limit the applicability to miniature devices.

In the experiment (see Fig. 2), two VCSELs at 795 nm with linear polarizations were placed adjacent to each other on a substrate such that the emitted light fields had mutually perpendicular polarizations. After passing through a quarter-wave plate, the respective light fields emerged with σ^+ and σ^- polarizations. The beams were then collimated by using a microlens, after which they were passed through a temperature-stabilized, microfabricated atomic vapor cell with an inner cavity volume of $\sim 1\ \mathrm{mm}^3$ containing enriched ^{87}Rb and 120 torr of an Ar–Ne buffer gas mixture. The light transmitted from the vapor cell was detected with a Si p-i-n photodetector. A set of Helmholtz coils was used to provide a longitudinal magnetic field. The two VCSEL currents were modulated at half the ground state hyperfine splitting frequency by a common frequency synthesizer. A variable microwave phase shifter was used to appropriately delay the phase of the microwave modulation on one of the VCSELs.

The CPT resonances observed when the microwave modulation on the two VCSELs was in phase and out of phase is shown in Fig. 3. A nearly complete destruction of the resonance was observed when the modulation signals were in phase, as expected. A remaining residual resonance was present mainly owing to an imperfect overlap between the two light beams in the experiment. Adequate care was taken here to ensure that the ratio of optical power in the two first-order sidebands in the two lasers were equal.

Figure 4 shows the CPT resonance amplitude, for both lasers together and for each laser individually, as a function of the total incident light intensity. At any particular intensity shown in the figure, the linewidth of the CPT resonance for two lasers was roughly equal to that for one laser. The observed result was compared with the theory based on an ideal open and closed Λ system.[9,19] The theory was fitted to the experimental data by using a common scaling factor and was found to be in good agreement.

To briefly examine the effectiveness of this and other similar techniques in directly improving the stability of CPT-based devices, we consider in general terms the advantage of a closed system over an open system. In devices based on continuous interrogation, the optimal light intensity is usually close to a value where the power-broadening contribution to the CPT linewidth is roughly equal to the zero-intensity linewidth. This is because for larger intensities the ratio of CPT amplitude to linewidth at best remains a constant while the noise on the photodetector increases. For lower optical intensities the ratio of CPT amplitude to linewidth decreases linearly or even faster with intensity. Although the FM–AM noise[20] also decreases linearly with intensity, the system can be

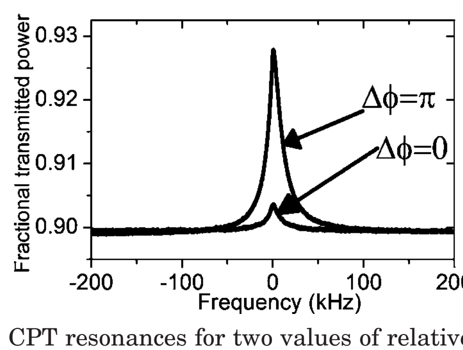

Fig. 3. CPT resonances for two values of relative modulation phase $\Delta\phi$.

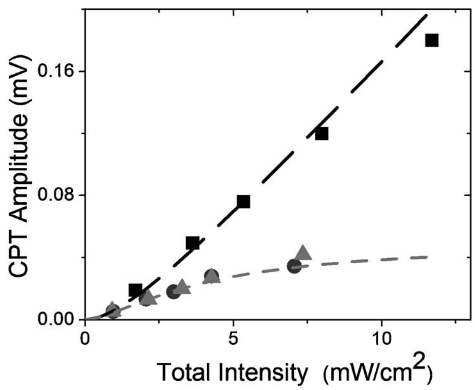

Fig. 4. CPT resonance amplitude versus intensity with optimal phase delay for the case of both fields (squares) and of a single field (circles, triangles).

quickly dominated by the photon shot noise[21] or the electronic noise, which decreases more slowly with intensity. Hence the performance of the clock degrades at both higher and lower intensities. In the experiment reported here, the power broadening becomes equal to the zero-intensity linewidth at an intensity of about $3.5\ \mathrm{mW/cm^2}$. From Fig. 4, it can be seen that at this intensity the CPT amplitude in the closed system is only larger by about a factor of 2 than that in the open system. Hence one expects to gain roughly a factor of about 2 in short-term frequency stability in an atomic frequency reference fully optimized with respect to other parameters. In essence, power broadening can eliminate the advantage that the large increase in signal amplitude provides at higher optical intensities for continuously pumped frequency references. From this viewpoint, Ramsey excitation of CPT resonances,[12,22] which is largely free from power broadening, may offer a way to take full advantage of the signal gains obtained with optical pumping techniques such as that described here.

In conclusion, we have demonstrated a novel technique for significantly improving the CPT resonance amplitudes in open Λ systems. The simplicity of this technique makes it practical to implement in miniature atomic devices and can also be used to prepare nearly pure, coherent superposition states in other miniature devices. To determine the true advantage that this and other similar techniques offer in improving the stability of the conventional continuously operated CPT-based devices requires careful analysis of all operating parameters. The technique proposed here is experimentally implemented by using a VCSEL and a microfabricated atomic vapor cell containing ^{87}Rb atoms with a Ne–Ar buffer gas mixture. The experimental results are compared with the theory[9,19] and are found to be in good agreement.

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