Fast Light Enhancement by Polarization Mode Coupling in a Single Optical Cavity

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ABSTRACT

We present an entirely linear all-optical method of dispersion enhancement that relies on mode coupling between the orthogonal polarization modes of a single optical cavity, eliminating the necessity of using an atomic medium to produce the required anomalous dispersion, which decreases the dependence of the scale factor on temperature and increases signal-to-noise by reducing absorption and nonlinear effects. The use of a single cavity results in common mode rejection of the noise and drift that would be present in a system of two coupled cavities. We show that the scale-factor-to-mode-width ratio is increased above unity for this system and demonstrate tuning of the scale factor by (*i*) directly varying the mode coupling via rotation of an intracavity half wave plate, and (*ii*) coherent control of the cavity reflectance which is achieved simply by varying the incident polarization superposition. These tuning methods allow us to achieve unprecedented enhancements in the scale factor and in the scale-factor-to-mode-width ratio by closely approaching the critical anomalous dispersion condition.

Keywords: Optical Resonators, Laser Gyroscopes, Coherent Optical Effects, Anomalous Dispersion, Fast Light

1. INTRODUCTION

Recent experiments using atomic Rb vapor as an intracavity anomalous dispersion, or fast light, medium have demonstrated that the scale factor and sensitivity of an optical cavity can be strongly enhanced as a result of mode pushing which provides a positive feedback to the cavity response.[1-5] The cavity becomes hypersensitive to variations in length at a critical value of the anomalous dispersion where a pole occurs in the cavity scale factor. The mode width does not increase to the same degree because of mode reshaping by group velocity dispersion, resulting in an overall increase in the scale-factor-to-mode-width ratio. These revelations have led to efforts to further develop these dispersion-enhanced cavities for applications such as increasing the precision of optical gyroscopes for inertial navigation,[1-8] increasing the sensitivity-bandwidth product for interferometric gravity wave detectors,[9-11] precision measurements of the Lense-Thirring frame-dragging effect,[7] increasing the delay-bandwidth product of data buffers without distortion,[12] the auto-stabilization of optical cavities,[13,14] and enhanced strain and displacement sensing.[15]

One drawback that has been pointed out for these atom-cavity systems, however, is that the increase in the scale-factor-to-mode-width ratio is accompanied by a substantial decrease in the output intensity as a result of the absorption of the atomic medium, thereby limiting the increase in the signal-to-noise.[16] Additional concerns are spatial and temporal variations in scale factor as a result of the temperature dependence of the atomic absorption, as well as the presence of intensity-dependent nonlinearities which complicate the calculation of the response, tend to reduce the scale factor, and limit the signal-to-noise by limiting the intensity of the input beam that can be applied.

Fortunately, the dispersion enhancement does not only occur for the case of an intracavity medium. An alternative and more fundamental way of looking at the "dispersion" enhancement is that it results from the coupling of resonant modes. In this view, the scale factor pole is simply an example of an exceptional point, commonly found in coupled systems described by non-Hermitian Hamiltonians, such as coupled oscillators having different loss rates. The dispersion

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enhancement can therefore be found in any physical system involving coupled oscillators near such an exceptional point. An attractive approach would therefore be to eliminate the intracavity atomic medium entirely and instead use the resonances of a second cavity of fixed length as the intracavity dispersive element. As discussed in a previous work, to achieve the required anomalous dispersion and enhance the scale-factor-to-mode-width ratio it is necessary to under-couple the individual cavities to each other and under-couple the entire system to the incident light, respectively.[17] In practice this is easy to achieve and results in a higher signal-to-noise because light that would have been absorbed and reradiated incoherently in all directions by the intracavity absorber is now coherently recycled by the additional cavity. Moreover this all-optical approach is entirely linear, does not suffer from the temperature dependency of the atomic absorption, and is not limited to operation at atomic resonance frequencies.

Producing a coupled cavity system with a stable relative detuning between the modes of two different cavities is not a simple proposition, however, because each cavity suffers from independent amounts of noise and drift. Implementation of such a scheme therefore requires the stabilization of one cavity to the other at some controllable offset. Moreover, there is no simple way to control the degree of coupling between the two cavities to tune the scale factor. While it is possible to use coupled fiber optic resonators with tunable couplers, these systems typically suffer from even greater noise and drift than do free space cavities.[18] A chief advantage of the atom-cavity systems, therefore, is the inherently stable resonant frequencies offered by atomic systems for creating the dispersion enhancement. In this paper, we present an alternative "coupled cavity" approach which relies on mode coupling between orthogonally polarized modes in a single cavity. The noise and drift are common mode rejected, because both polarization modes, i.e., "cavities", share the same optical path, resulting in a stable relative mode detuning which can be controlled by an intracavity variable retarder aligned with one of the polarization modes. Mode coupling is controlled by the simple rotation of an intracavity half-wave retarder. In this manner, the enhancement in cavity scale factor is reproducible and stable.

An additional benefit of this arrangement is that it allows investigation of an alternative method for tuning the scale factor, via coherent control of the cavity reflectance. In this case a second input beam is directed into the cavity such that it coherently interferes with the first input beam.[5,19] The tunability of the scale factor then arises from the interference between the transmission of the first input and the reflection of the second from the cavity. This approach is closely related to the recently demonstrated phenomenon of coherent perfect absorption,[20,21] but differs in that does not require increasing the cavity absorptance to unity. Instead only a slight modification of the cavity absorptance is required, which can be accomplished simply by varying the relative intensity of the second beam while keeping its relative phase constant. This method has the advantage over other scale factor tuning methods in that it is completely linear, occurs irrespective of the choice of intracavity medium, and occurs on the fast timescale of the cavity buildup time. Moreover, the scale factor can be tuned without needing to disturb or modify anything inside the cavity, which could diminish the cavity performance. This scheme is difficult to implement, however, using two different cavities because the introduction of a second coherent input beam effectively means employing an interferometer. The resulting phase fluctuations in the interferometer, along with the required active stabilization of the coupled cavities, makes the use of two different cavities impractical for demonstrating this method of tuning the scale factor. The arrangement presented herein solves these problems. The two coupled cavities are replaced by a single cavity whose polarization modes couple, enabling interference to occur between the two orthogonally polarized inputs. Hence, this arrangement allows two "inputs" into the cavity whose phase difference is stable, being determined solely by the input polarization, without having to actually inject a second coherent beam, and it results in common mode rejection of cavity noise.

2. EXPERIMENTAL SETUP

An external-cavity diode laser having a linewidth of <1 MHz at 780 nm was used to scan over the modes of an L = 30 cm, 1 GHz free spectral range (FSR) optical ring cavity to obtain polarized reflection and transmission spectra as shown in Fig. 1. An intracavity liquid crystal (LC) variable retarder whose slow (tuning) axis was aligned horizontally with the *p*-polarization mode was used to introduce a controllable detuning between the two orthogonal polarization modes of the cavity. We will refer to the coupled and uncoupled detunings between the two polarization modes as Δ and δ, respectively. The enhancement in the cavity scale factor can then be defined as $S = d\Delta / d\delta$. An intracavity half-wave plate whose fast axis was aligned close to the vertical direction was used to couple the polarization modes. The coupling can be turned off by positioning the wave-plate in the vertical (or horizontal) direction and is maximized at 45 degrees at which point the cavity FSR is essentially halved.

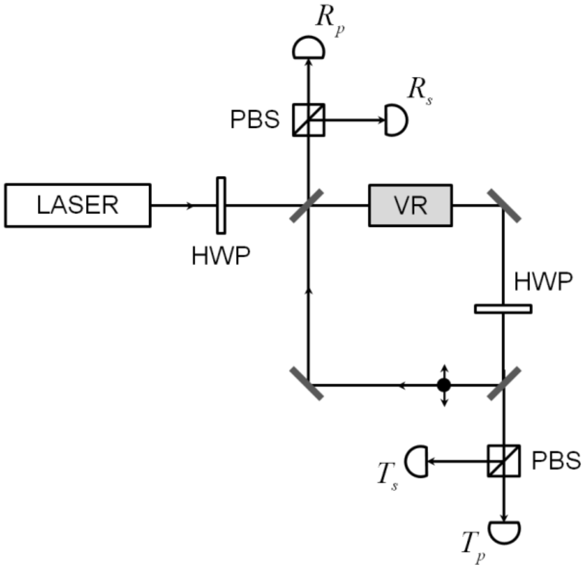

Fig. 1. A tunable diode laser is scanned over the modes of a passive ring cavity to obtain s- and p-polarized reflection and transmission spectra. PBS = polarizing beam splitter. The cavity polarization modes are detuned by a variable retarder (VR) and coupled by a half-wave plate (HWP). The linear input polarization is controlled by a half-wave plate external to the cavity.

3. RESULTS AND DISCUSSION

Spectra were recorded with and without mode coupling, at a variety of detunings as one polarization mode was tuned across the other. A larger number of spectra were taken near the detuning where the two polarization modes were co-resonant by applying a nonlinear voltage step on the LC retarder. An automated peak finding program was written to obtain the frequencies of the mode peaks as well as their FWHM mode widths from each of the experimental spectra with the coupling turned on and off resulting in the scale factor plots shown in Fig. 2 for the modes in reflection. Each data point along a given curve in the figure represents a different liquid crystal voltage. The two “cavities” were under-coupled to each other and the system was under-coupled to the incident light as required to obtain an enhancement in the scale-factor-to-mode-width ratio. The asymmetry and offset of the enhanced scale factor region from $\delta = 0$ is a result of a slight mode asymmetry that occurs as a result of cavity misalignment, which effectively causes the detuning between the modes to change as the coupling is varied by rotation of the waveplate. The cavity finesse was measured from the uncoupled s-polarized reflection spectra to be $F = 9$. The finesse of the uncoupled p-polarized modes was only slightly smaller.

To demonstrate that the scale factor can be tuned by coherent control of the cavity reflection, the incident linear polarization angle θ_i (with respect to the vertical) was varied while keeping the angle of the coupling wave-plate θ_c constant. The relative amplitude between the *s*- and *p*-polarized inputs was determined from the relation $\beta = \cos\theta_i / \sin\theta_i$. Three input angles were chosen: $\theta_i = 45^\circ$, $\theta_i = 30^\circ$, and $\theta_i = 24^\circ$, corresponding to $\beta = 1.00$, $\beta = 1.73$, and $\beta = 2.25$, respectively, so that more s- than p-polarized light was incident on the cavity. Importantly, as β is varied, the symmetry of the mode spectrum is preserved only when the relative phase of the inputs is $\varphi = 0$ or π. For linearly polarized incident light, this condition is automatically satisfied. The relative phase is either zero or π, depending on the orientation of the input wave-plate θ_i with respect to that of the coupling wave-plate θ_c. In our case the angle of the coupling wave-plate was set to $\theta_c = 1^\circ$, therefore $\varphi = 0$.

Note that as the value of β increases, the scale factor also increases due to the interference with the second input beam which effectively attenuates the mode, increasing the effect of the anomalous dispersion introduced by the coupling to the s-polarized cavity mode. In Fig. 2, at $\theta_i = 45^\circ$ the scale factor is not enhanced, i.e., $S = 1.0$, whereas at

$\theta_i = 24^\circ$ the enhancement was measured to be $\bar{S} = 8.3$ by making a linear fit to only the points residing in the linear regime close to the resonance. This procedure results in an average (rather than the maximum) scale factor in the regime close to resonance. Therefore, without modifying or disturbing any intracavity elements the scale factor can be tuned across a large range merely by changing the input polarization superposition. It is even possible to tune across the critical anomalous dispersion (CAD) condition and split the mode if β is made sufficiently large that the scale factor pole is exceeded (not shown).

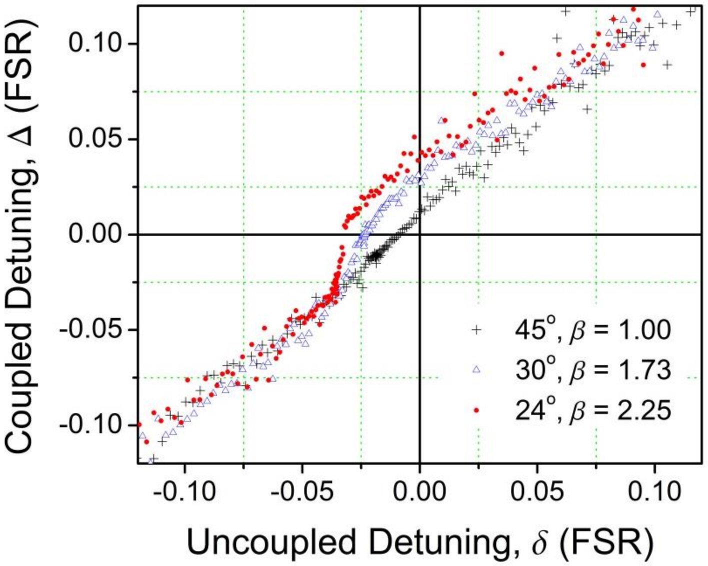

Fig. 2. Coherent control of the cavity scale factor. The scale factor increases as the relative amplitude of the second input beam β increases via rotation of the input polarization.

Fig. 3 shows the large enhancement in the scale factor that occurs near the CAD condition. The cavity was realigned to minimize misalignment, the transmission path was eliminated by replacing the output coupler with a high reflector, and the coarse wave-plate mounts were replaced with precision rotation mounts to hone in on the scale factor pole. Note that the offset of the data from $\delta = 0$ has the opposite sign and is now smaller than it was in Fig. 2 as a result of the improved alignment. The new value of the finesse measured for the uncoupled *s*-polarized modes was $F = 10$. The input polarization was set to $\theta_i = 24^\circ$ ($\beta = 2.25$), the coupling wave-plate was set to $\theta_c = 3^\circ$, and the wave-plates were finely tuned over a few arc minutes until the spectrum, observed on an oscilloscope, came very close to splitting. Data were then recorded over a small region around $\delta = 0$. The resulting average scale factor near co-resonance was measured to be $\bar{S} = 28.3 \pm 1.0$. Importantly, the mode width of the *p*-polarized modes increased by only $\bar{W}_p = 1.85 \pm 0.003$ compared to its value away from the co-resonance condition, whereas the mode width of the *s*-polarized modes was almost unchanged at $\bar{W}_s = 0.94 \pm 0.002$. The mode width does not increase to the same degree as the scale factor owing to group velocity dispersion, which is present because the mode widths of the *s*- and *p*-polarized modes are comparable. Hence, the scale-factor-to-mode-width ratio was enhanced by $\bar{S} / \bar{W}_p = 15.2 \pm 1.0$.

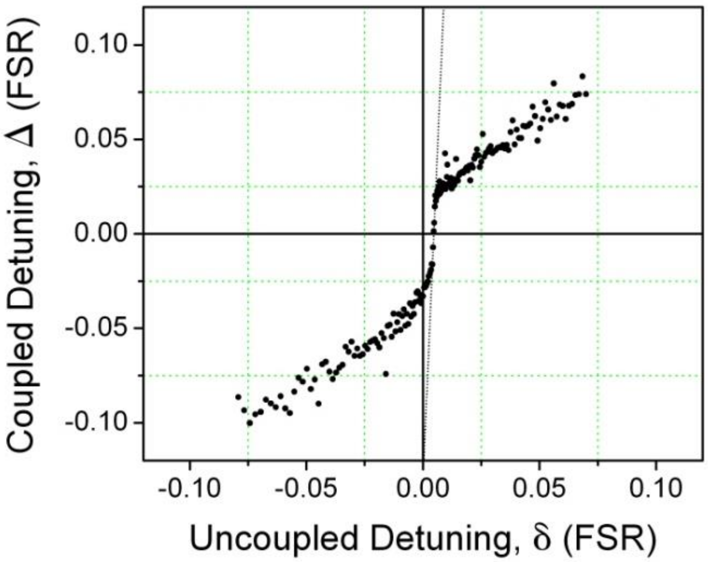

Fig. 3. A pole in the scale factor becomes evident near the critical anomalous dispersion condition. The dotted line is the result of a linear fit to points lying in the region of enhanced scale factor.

4. CONCLUSION

We have demonstrated an entirely linear all-optical method of dispersion enhancement using mode coupling between the orthogonal polarization modes of a single optical cavity. Eliminating the atomic medium decreases the variation of the scale factor with temperature, reduces absorption and re-emission of radiation in the cavity, and eliminates saturation and hyperfine pumping effects, thereby increasing the signal-to-noise. This approach is not limited to operation at atomic resonance frequencies. Moreover, the use of a single cavity results in common mode rejection of noise and drift, enabling demonstration of the scale factor enhancement without the need to mutually stabilize two cavities. By eliminating variations that occur in the relative phase of two cavity input beams, this arrangement also enables demonstration of coherent control of the cavity scale factor. The advantage of this method is that it enables rapid tuning (fundamentally limited only by the cavity buildup time) of the scale factor to the optimal fast light condition without having to disturb anything inside the cavity. We have shown that the scale factor can be readily tuned either by rotating the intracavity coupling half-wave plate, or by rotation of the input polarization. These tuning mechanisms have allowed us to closely approach the CAD condition, achieving a scale factor enhancement of $\bar{S} = 28.3 \pm 1.0$ and a scale-factor-to-mode-width ratio of $\bar{S} / \bar{W}_p = 15.2$. Automation of the peak finding procedure and the use of nonlinear data steps has allowed substantially more data to be collected in the region of scale factor enhancement, reducing significantly the uncertainty in comparison with our previous measurements.[4] On a final note, for the purposes of modeling the two coupled polarization modes can be treated as if they were the modes of two coupled cavities. We have performed such an analysis and plan to present this work in a future publication.

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