

Improving Optical Gyroscope Sensitivity Using a Fast Light Regime

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1 Abstract

Severalfold improvements to optical gyroscope sensitivity are predicted for fast light regimes ($n_g < 1$). The feasibility of these improvements will be evaluated in a regime in the Rubidium spectrum, with an engineered negative dispersion to achieve fast light, and a suitably high gain to allow for lasing within the cavity.

2 Introduction

2.1 The Sagnac effect

The basic principle of operation for laser gyroscopes is based on the Sagnac effect. The Sagnac effect describes a change in optical path length in a ring cavity due to rotation.

$$\Delta L = \frac{2\pi R^2 \Omega}{c + R\Omega} \quad (1)$$

Where ΔL is the change in path length, R is the radius of the cavity, c is the speed of light, and Ω is the gyroscope angular velocity. In the limit where $R\Omega \ll c$ the resonant frequencies of the cavity for two counter propagating beams are separated from each other.

$$\Delta f_{empty} = \frac{2A\Omega}{\lambda P} \quad (2)$$

Where Δf_{empty} is the separation of the two frequencies (under the assumption that no dispersive medium is present in the cavity), A is the area of the gyroscope cavity, Ω is the angular velocity of the gyroscope, P is the perimeter of the gyroscope cavity, and λ is the wavelength of light in the cavity.

2.2 Laser Gyroscopes

Laser gyroscopes exploit the Sagnac effect in a ring cavity to measure angular velocity. The measurement is done by introducing a gain medium into the cavity. The overall gain of the system will only exceed unity near the cavity resonances. If the line width of the gain medium is small enough then only a single cavity resonance will be amplified. Therefore a rotating cavity will automatically lock to the two resonances for each direction of propagation. The difference of the two frequencies can be measured using heterodyne detection.

2.3 Fast Light

The group index of light in a dispersive medium is given to first order by Eq.3

$$n_g = n_0 + \omega \frac{\partial n}{\partial \omega} \quad (3)$$

where n_g is the group index, n_0 is the refractive index, ω is the frequency of light, and $\frac{\partial n}{\partial \omega}$ is the dispersion. Like the refractive index, the group index is related to the group velocity

$$v_g = \frac{c}{n_g} \quad (4)$$

The group velocity (v_g), describes the velocity at which the envelopes of an optical signal can propagate. In contrast to the phase velocity, the group velocity can be superluminal under certain conditions as it does not necessarily carry information. This can be achieved by having a sufficiently negative dispersion such that $n_g < 1$, light under this condition is referred to as fast light.

Theory predicts that the changes in the resonant frequencies due to a change in length is dependent on group velocity. The frequency splitting in a dispersive cavity can be related to the frequency splitting in the empty cavity (Eq.2) by Eq.5¹

$$\Delta f_{dispersive} = \frac{\Delta f_{empty}}{n_g} \quad (5)$$

A particular N-bar four wave mixing Scheme in the ^{87}Rb atomic structure has been selected as a particular candidate for a gain medium that can achieve fast light conditions. Two pump fields tuned to 795nm (D1) and 780nm (D2) interact with the rubidium atom and generate two new fields, each detuned by 6.8GHz from each of the pump fields. (See Figure.1) ^{2,3}

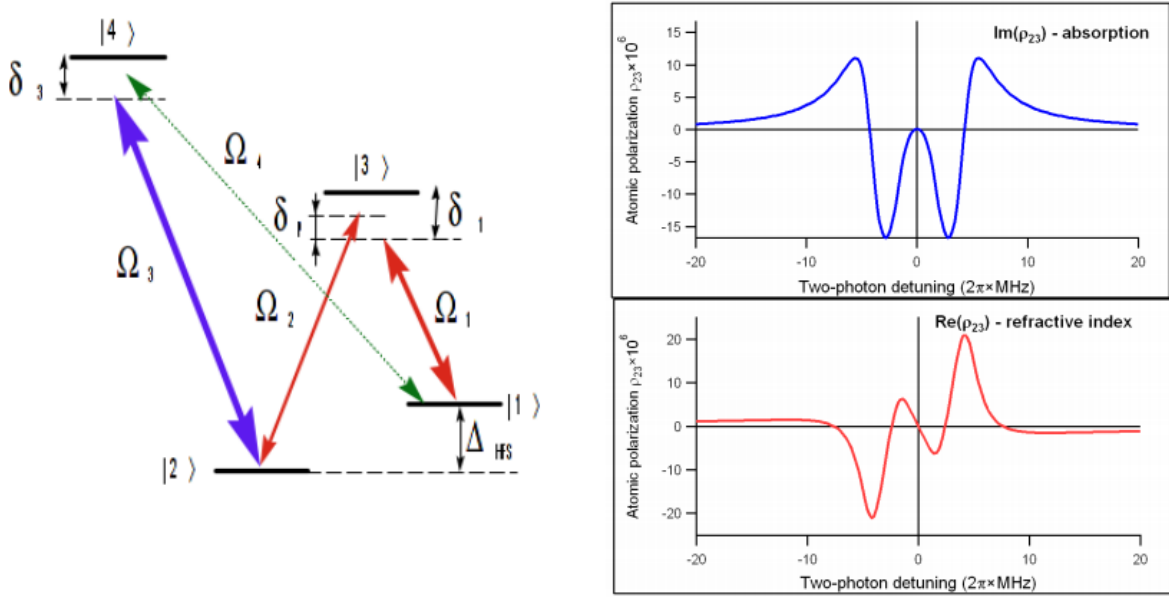


Figure 1: (Right) A simplified N-bar Four wave mixing scheme to be tested as a medium provide gain for lasing as well as the conditions for fast light. (left) Predicted absorbtion and Phase index relations for this simplified four wave mixing scheme.

Theory predicts that this type of four wave mixing scheme should have both a suitably high gain to achieve lasing as well as a sufficiently negative dispersion to achieve fast light.

3 Experiment

3.1 Setup

The pump fields are injected into the cavity through optical fibers. The pump fields only pass through the Rubidium cell once and are kept out of the cavity using polarizing beam splitters so that only the generated are sustained in the cavity. A mirror that forms the cavity is fixed to a PZT so that the length of the cavity could be modulated and stabilized (See Figure 2).

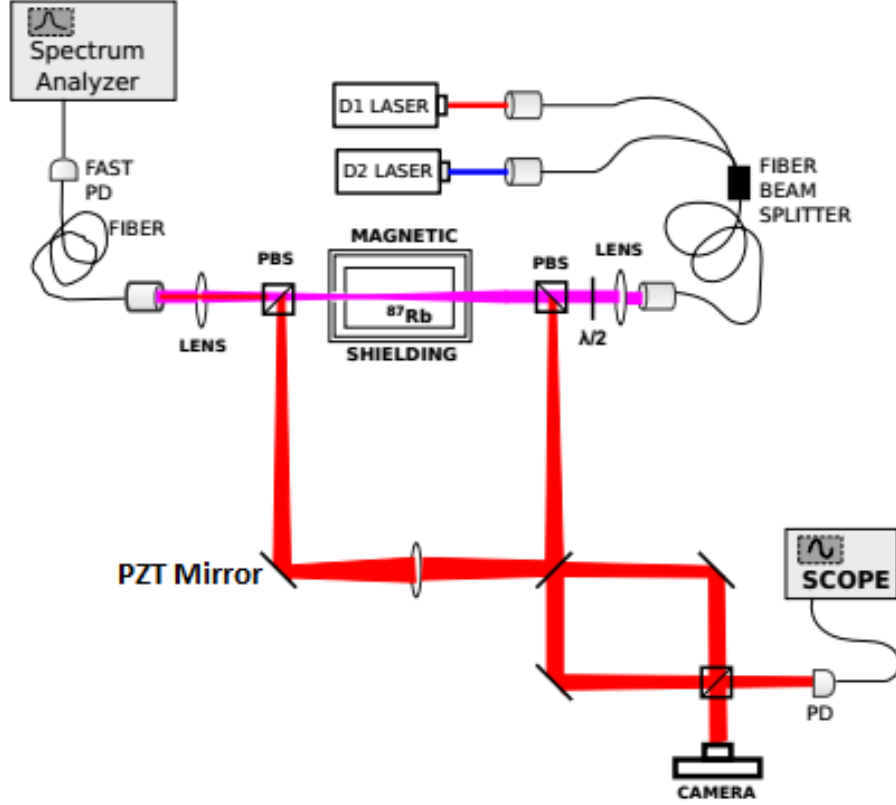


Figure 2: A simplified diagram of the cavity used in this experiment.

A quarter wave plate was added immediately after cell so that some of the lasing field could escape the cavity to allow measurement. Unfortunately introducing losses into the system to allow for measurement inherently decreases the finesse of the cavity which could reduce the sensitivity of the Gyroscope.

The D1 pump field and the cavity both suffered from instabilities. A reference cavity and a PI-controller were introduced to stabilize the D1 pump. To stabilize the ring cavity a 3rd, far detuned, field was injected into the cavity. This third field is used to generate an error signal to stabilize the cavity. The frequency of this laser is modified to control the length of the cavity.

3.2 Measuring Pulling Factor

The quantity being measured in this investigation is called pulling factor. Pulling factor is the ratio of the Frequency splitting measured in the dispersive cavity and the hypothetical splitting in an empty cavity (Eq.6)

$$PF = \frac{\Delta f_{dispersive}}{\Delta f_{empty}} \quad (6)$$

pulling factor is measured using heterodyne detection between the pump field and the lasing field, yielding a heterodyne signal around Rubidium's hyperfine-splitting frequency of 6.83GHz(See Figure 3). Additionally, beat note amplitude is related to the power of the lasing field amplitude. The beatnote

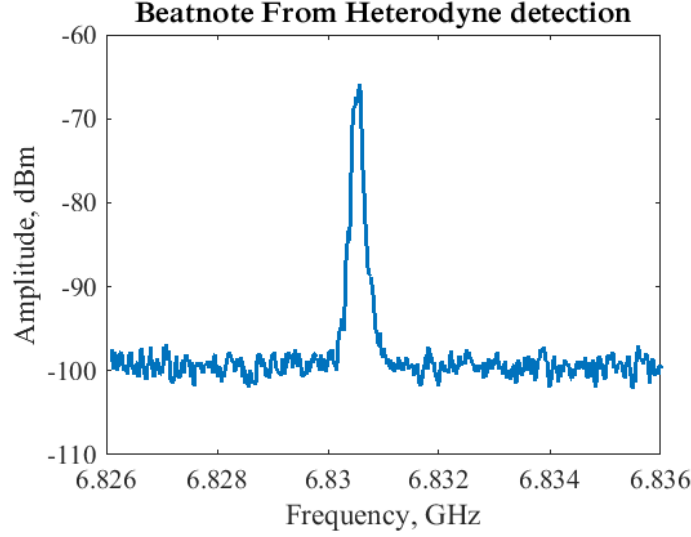


Figure 3: Typical Beat note generated by mixing pump and lasing fields centered near 6.83 GHz.

position is measured using the spectrum analyzer at various cavity lengths so that a trend can be extracted (See Figure 4)

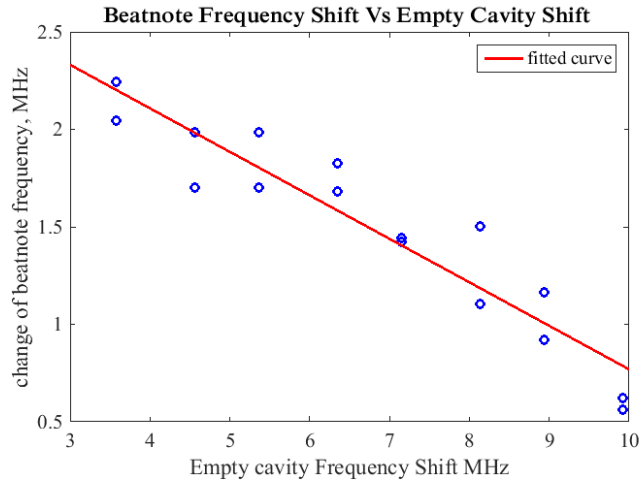


Figure 4: Beatnote measurements at different cavity lengths

The pulling factor is calculated by fitting a line to the data, the slope of the fit is the pulling factor.

4 Results

4.1 Initial D1 Detuning Dependence

The first parameter dependence to be evaluated systematically was the D1 detuning. The D2 was tuned to the peak generation at $F_g = 2 \rightarrow F_e = 1$ transition with a power of 2mW D1 had a power of 5mW. The dependence of pulling factor and beat note amplitude were measured (See Figures 5 and 6)

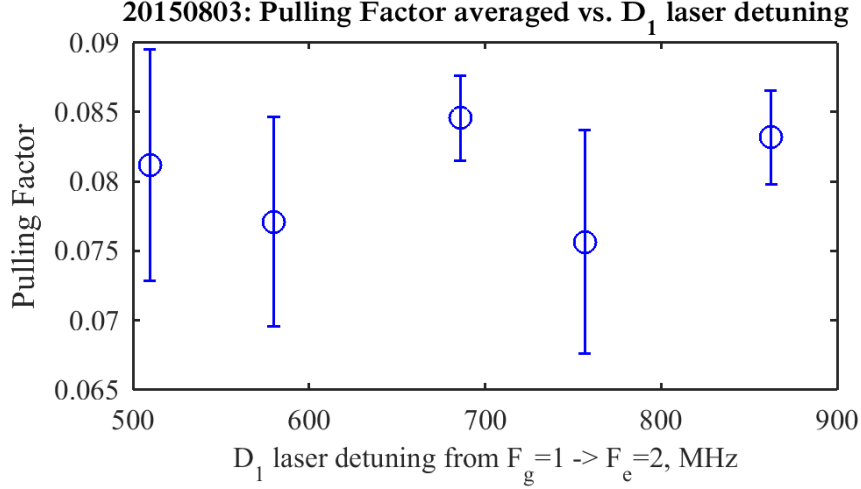


Figure 5: Initial Dependence of pulling factor on D1 pump detuning

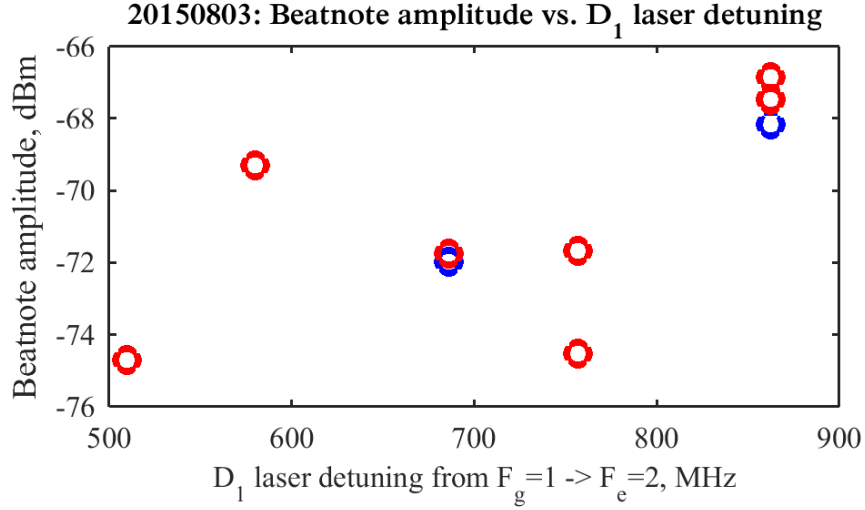


Figure 6: Initial Dependence of beat note amplitude on D1 pump detuning

At these conditions it did not appear that any interesting behavior was present because the variations in pulling factor were minute.

4.2 Initial D2 Detuning Dependence

After displaying insignificant dependences at the initial conditions, D2 dependence was evaluated. The D1 pump was tuned 314 MHz away from the $F_g = 1 \rightarrow F_e = 2$ transition with a power of 5mW, D2 had a power of 2mW. The dependences of pulling factor and beat note amplitude were measured (See Figures 7 and 8)

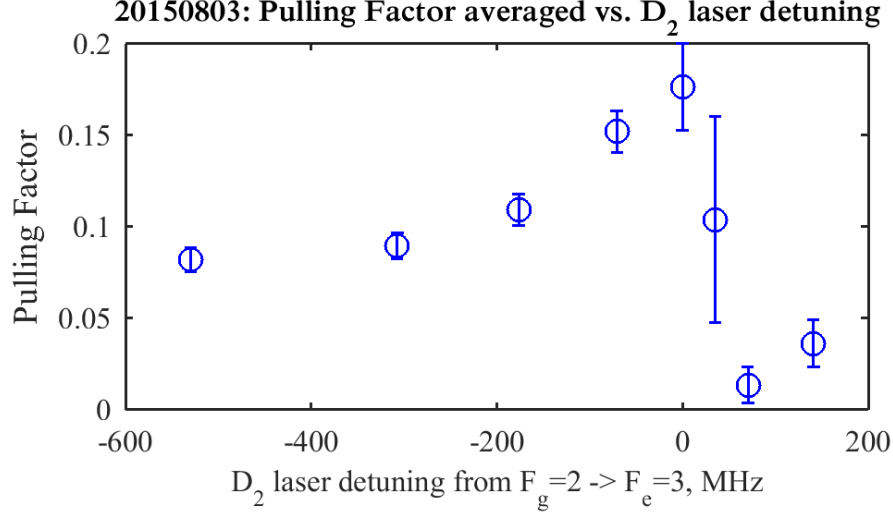


Figure 7: Initial Dependence of pulling factor on D2 pump detuning

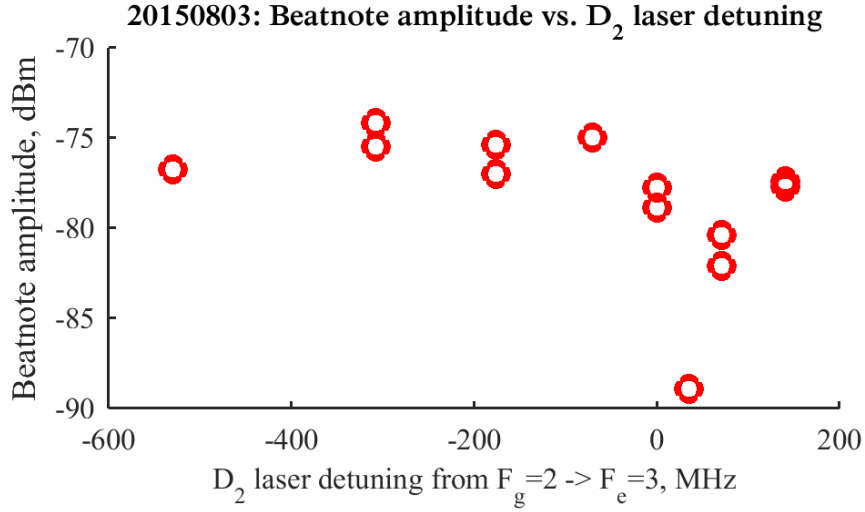


Figure 8: Initial Dependence of pulling factor on D2 pump detuning

A clear local maximum is present around zero D2 detuning and it appears to coincide with a decrease in beat note amplitude however that connection has not yet been proven to be significant. However it is clear that the local maximum pulling factor existed when D2 was tuned to the $F_g = 2 \rightarrow F_e = 3$ transition and not at the maximum generation.

4.3 Final D1 Detuning Dependence

After maximizing pulling by varying D2 the dependence of pulling on the detuning of the D1 pump was re measured. The D2 pump was tuned to the $F_g = 2 \rightarrow F_e = 3$ transition with a power of 2mW, D1 had a power of 5mW. The dependences of pulling factor and beat note amplitude were measured(See Figures 9 and 10)

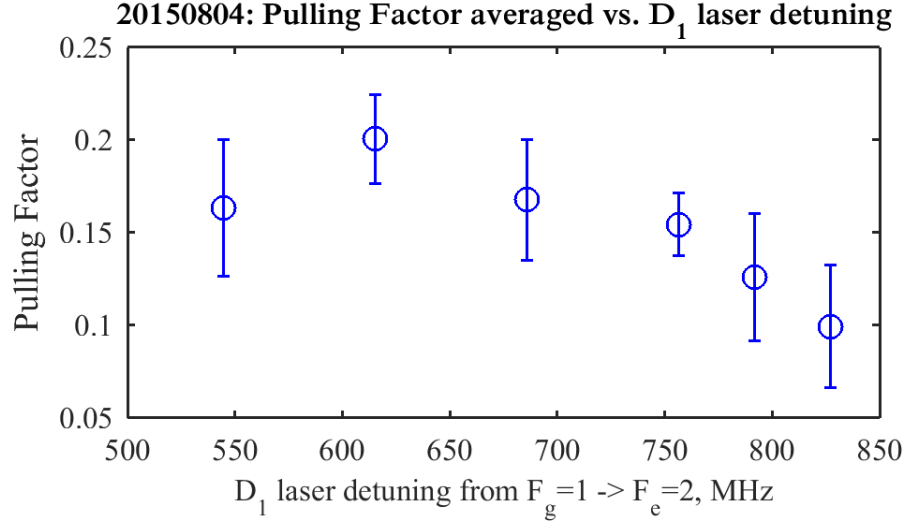


Figure 9: Final Dependence of pulling factor on D1 pump detuning

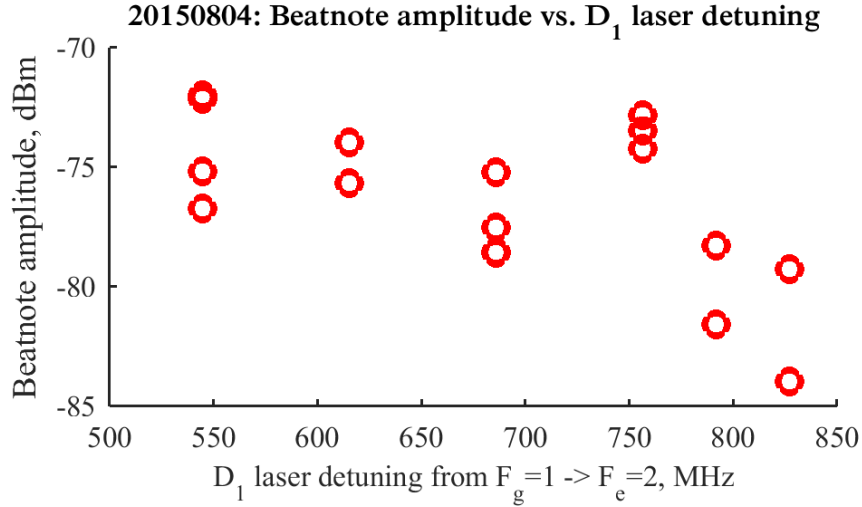


Figure 10: Final Dependence of pulling factor on D1 pump detuning

With these new D2 pump conditions, the dependence on the D1 pump is more noticeable. A new maximum for pulling factor exists around 600 MHz detuning from the $F_g = 1 \rightarrow F_e = 2$ transition.

4.4 D2 Power Dependence

Other factors effect the properties of the four wave mixing Scheme. The first investigated parameter was the D2 Power. The D1 pump was tuned 314 MHz away from the $F_g = 1 \rightarrow F_e = 2$ transition at a power of 5mW. the D2 pump was tuned to the $F_g = 2 \rightarrow F_e = 3$ transition, where maximum pulling factor was measured. The dependences of pulling factor and beat note amplitude were measured(See Figures 11 and 12)

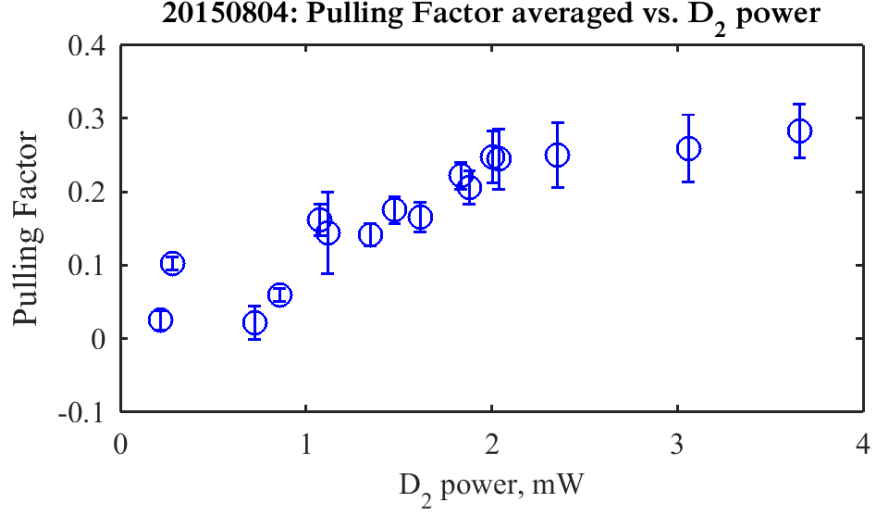


Figure 11: Final Dependence of pulling factor on D2 pump power

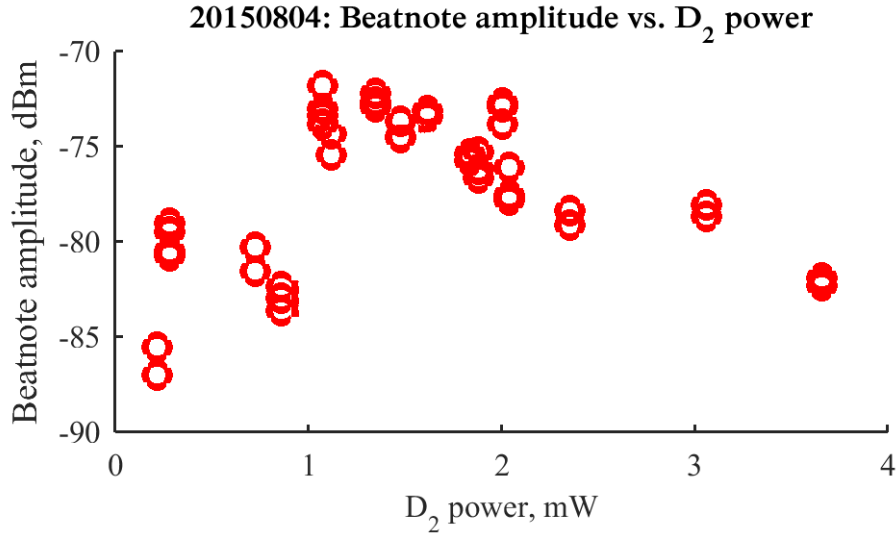


Figure 12: Final Dependence of pulling factor on D2 pump power

A positive relationship between D2 power and pulling factor is clearly visible but no maximum is definitely present so more power is needed to explore the relationship in its entirety. Again the increase appears to coincide with a reduction in beat note amplitude.

4.5 Temperature Dependence

Temperature directly effects the density of the vapor in the vapor in the cell. The density of the RB⁸⁷ is theorized to have an effect on pulling factor. The temperature was controlled via a temperature controller. The pump fields were tuned to maximum generation, and pulling factor was measured at various temperatures (Figure 13)

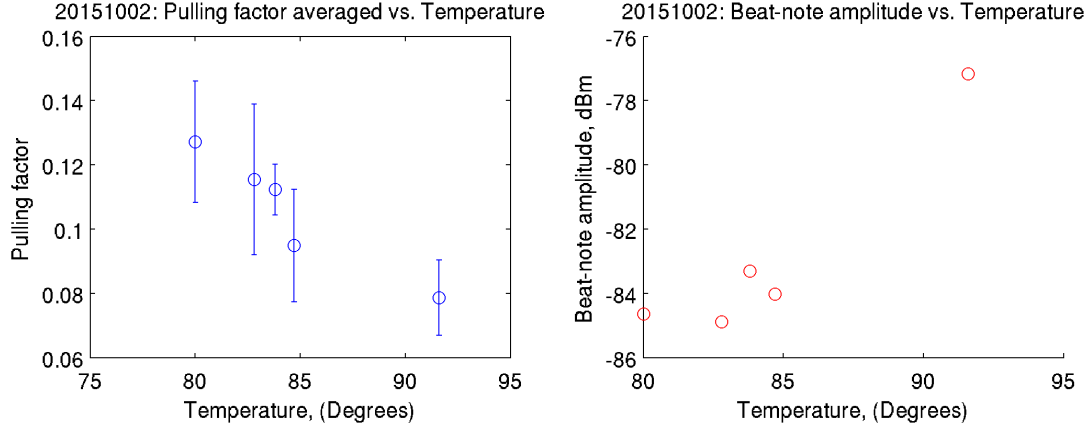


Figure 13: Dependence of pulling factor on Temperature

At this detuning temperature increases caused pulling factor to decrease slightly. While causing the generation amplitude and beat note amplitude to increase.

4.6 Finesse

Finesse is also theorized to have an effect on pulling factor. In this experiment some losses are required to measure the generated field, therefore higher finesse make measurement more difficult. However a high finesse is hypothesized to have strong contributions to pulling. To test the dependence, the pump fields were tuned to maximum generation and measurements were taken after varying the finesse (figure 14). Finesse was controlled by rotating a quarter wave plate that controls losses in the generated field inside the cavity.

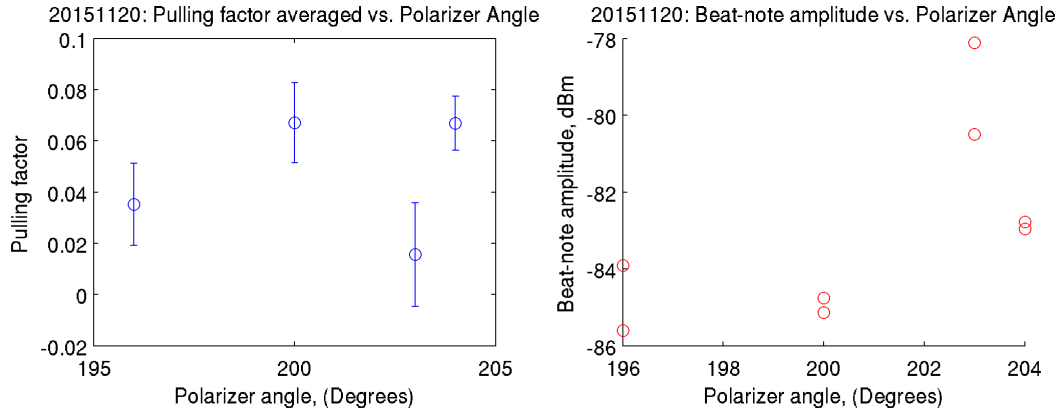


Figure 14: Dependence of pulling factor on quarter wave plate position.

The wave plate rotations conducted, represent a fairly wide range in finesse (nearly a 50 percent

variation). The pulling factors remain relatively low (lingering around 0.05) the moderate variations suggest that the dependence on finesse is nearly negligible under these circumstances.

5 Conclusions

Tunning various parameters can yield large increases in the pulling factor. From initial measurements of pulling factor less than 0.1 improvements brought the pulling factor to around 0.3. Temperature increases led to moderate decreases in pulling factor, while making measurement easier by increasing beat note amplitude. Changes in Finesse had little to no effect on pulling factor. While these values are still less than the target pulling factor of greater than 1, these dependences represent only a fraction of the parameter space. D2 power still needs to be explored at higher powers, D1 power needs to be explored and different choices of lasing modes still need to be evaluated. Evaluations of the effects of temperature and finesse need to be more deeply evaluated in different regimes. The parameters are not independent of each other so varying only one parameter in each experiment is not sufficient to determine all of the dependences. Further optimization may yield the targeted high pulling factors.

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7 References

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