Optical cavity for enhanced parametric four-wave mixing in rubidium

E. Brekke and S. Potier
Physics Department, St. Norbert College, De Pere, WI 54115

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We demonstrate the implementation of a ring cavity to enhance the efficiency of parametric four-wave mixing in rubidium. Using an input coupler with 95% reflectance, a finesse of 19.6±0.5 is achieved with a rubidium cell inside. This increases the circulating intensity by a factor of 5.6±0.5, and through two-photon excitation on the 5s\(_{1/2} \rightarrow 5d\_{5/2}\) transition with a single excitation laser, up to 1.9±0.3 mW of power at 420 nm is generated, 50 times what was previously generated with this scheme. The dependence of the output on Rb density and input power has been explored, suggesting the process may be approaching saturation. The blue output of the cavity also shows greatly improved spatial quality, combining to make this a promising source of 420 nm light for future experiments.

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I. INTRODUCTION

Four-wave mixing continues to be an active area of research, with applications in a number of different contexts and materials. Currently, four-wave mixing is being pursued in applications including quantum information \[1, 2\], Rydberg States \[3–5\], single-photon sources \[6\], and optical gyroscopes \[7\]. It has been examined in a wide range of contexts, including hollow core fibers \[8\], cold atoms \[9\] and thermal vapors of rubidium and cesium \[10, 11\].

One of the main applications of four-wave mixing continues to be frequency up-conversion in rubidium, both using a two-step excitation process \[12–15\], and using a single laser for two-photon excitation \[16, 17\]. Extensive work has already been done to better understand the linewidth and frequency characteristics of the resulting light \[18–20\]. Recently the infrared light generated has also been examined \[21, 22\], and this process has been used to investigate the transfer of angular momentum \[23, 24\]. Several improvements have been made to the two-step process, including optical pumping \[25\], optimizing excitation frequency \[14\], high input powers \[22\], and using a cavity for the light produced \[26\], leading to output powers on the order of a mW. Meanwhile, the two-photon process has been limited to either pulsed systems or low output powers.

In this paper we demonstrate the implementation of a ring cavity to dramatically increase the power generated at 420 nm for parametric four-wave mixing in rubidium using a single laser excitation scheme. Using a low-finesse build up cavity for the 778 nm excitation light, the circulating intensity was increased by a factor of 5.6±0.5. This led to an increase in blue power by over two orders of magnitude, with a maximum power achieved of 1.9±0.3 mW, comparable to the highest output powers achieved in the two-step process. We have investigated the scaling of the output power with cell temperature and input intensity, as well as investigated the optimal parameters for the cavity. This technique presents a simple and attractive method for the generation of tunable far infrared light and blue light near the 5s\(_{1/2} \rightarrow 6p\_{3/2}\) transition in rubidium.

II. EXPERIMENTAL SETUP AND CAVITY DESIGN

Our experimental setup is schematically illustrated in Fig. 1. A single ECDL laser at 778 nm excites the two photon 5s\(_{1/2} \rightarrow 5d\_{5/2}\) transition in rubidium. The frequency control and tapered amplifier system have been described previously \[16\]. Amplified spontaneous emission and four-wave mixing in rubidium result in generated beams at 5.23 \(\mu\)m and 420 nm, with the relevant energy levels shown in Fig. 2. Here, we introduce a ring cavity surrounding a heated rubidium cell, to increase the
circulating intensity and dramatically increase the power generated in the non-linear four-wave mixing process.

![Energy levels involved in the FWM process. Two-photon excitation is accomplished using a single 778 nm ECDL on the $5s_{1/2} \rightarrow 5d_{5/2}$ transition. The resulting process produces coherent and collimated beams at 5.23 $\mu$m and 420 nm.](image)

The ring cavity is designed to focus the beam to a small waist inside a heated rubidium cell. Typical Pyrex cells have transmissions in the 80-90%, limiting the possible finesse of the cavity. A 95% reflectance input coupler was used to increase the circulating intensity in the cavity, with the other three mirrors reflecting more than 99.5% at 778 nm. The output coupler has more than 85% transmission at 420 nm. The total circulating intensity inside the cell at maximum is given by

$$I_c = \frac{1 - R}{1 - 2\sqrt{RT_c} + RT_c}, \quad (1)$$

Where $I_c$ is the circulating intensity, $I_0$ is the incident intensity, $R$ is the reflectivity of the input coupler, $T_c$ is the transmission through the cell, with the reflectivity of the other mirrors approximated as 100%. The transmission through our cell was 86%, and a plot of the maximum circulating intensity vs input coupler reflectance is shown in Fig. 3. The current work was done with a reflectance of 95%, giving a theoretical intensity gain of 5.2. Further optimization should be possible with an even lower reflectance at the optimal value of 86%.

To measure the finesse and circulating power in the cavity, a photodiode was used to examine the reflectance off the input coupler, which is combined with the transmission of the circulating light, as shown in Fig. 4. As the piezo voltage is varied, certain cavity lengths will give constructive interference in the cavity. The cavity had a finesse of 19.6±0.5, and gave a circulating power of 5.6±0.5 times the original, consistent with theoretical expectations.

![Finesse and circulating power in the cavity](image)

**III. RESULTS AND ANALYSIS**

It is expected that the gain for the four-wave mixing process would grow as the number of atoms in the $5d_{5/2}$ state, giving exponential dependence of the blue power on this population. If the process is far from saturation, we also expect exponential dependence of the blue power on the excitation intensity. We have measured the blue power generated as a function of the input power, with the data shown in Fig. 4. At low input powers, this dependence is consistent with exponential gain, but at high powers it trends toward a linear dependence. This could be an indication that the process is approaching a saturation point, or that competing processes are becoming significant.

Changing the temperature of the cell allows control of the density of rubidium atoms, and allows further exploration of the possible onset of saturation. Figure 5 shows the blue power as a function of the Rb density. The density is limited, corresponding to temperatures under 180°C, in order to prevent alkali reaction with the cell walls. Here, the growth in blue power at high densities is clearly suppressed. It has previously been observed that at higher temperatures competing processes may limit the successful production of blue light.

Both the intensity and temperature dependence suggest that we are approaching the saturation point of the four-wave mixing process. Eventually, the process would...
be limited when the two-photon excitation rate through the 5p level, $\Omega^{(2)}_{5s\rightarrow5p\rightarrow5d}$, is equal to the two-photon excitation rate through the 6p level, $\Omega^{(2)}_{5s\rightarrow6p\rightarrow5d}$ [27]. At this point the output power would only scale linearly with the input power. Further investigation into the cause of saturation of the system remains an intriguing area of research.

Through the use of this build-up cavity, the 420 nm output power reaches as high as 1.9±0.3 mW, comparable to the highest powers achieved with the two-step process [22, 26]. This output power is 50 times the power achievable without the cavity. Though there are signs of saturation, further gains could be made through increased input power, cavity reflectivity optimization, or using an additional cavity for the blue output [26].

IV. DISCUSSION AND CONCLUSIONS

The presence of the ring cavity provides significant power gains and an excellent spatial profile while maintaining a fairly simple experimental system. There is still only one diode laser needed for the process, and the lack of temperature dependence to the phase matching criteria makes this system much easier to use than a standard frequency doubling crystal.

The presence of the cavity does make it difficult to access the cell with an optical pumping beam, which has been shown to be successful elsewhere [25]. This could still be accomplished either by slightly non-collinear alignment of the pumping beam, or by using a cavity resonant for each frequency. Even without these, however, the intensity output gained from the cavity is more than 10 times what could be expected from optical pumping.

Recently it has been observed that a resonant cavity for the generated blue light increases output power and reduces the linewidth for the outgoing beam [26]. It could be a beneficial adaptation to construct a cavity which is
resonant for both 778 nm and 420 nm around the rubidium cell. The current work has not investigated the linewidth properties of the generated light, but this also remains an area of interest for the future.

The output power from this system is comparable to that generated in the two-step scheme using lasers at 780 and 776 nm. While the use of a cavity removes some of the simplicity of this format, it still makes use of a single excitation frequency and produces an easily controlled output frequency [20] due to the large intermediate state detuning. If a sapphire cell is implemented, the resulting beam at 5.23 \( \mu \)m could be used, which is expected to have hundreds of \( \mu \)W available. The resulting 420 nm beam is tunable around the rubidium 5s_{1/2} \rightarrow 6p_{3/2} \) transition, and so presents an excellent candidate for use in future experiments where rubidium is excited to high principle quantum numbers.

In conclusion, we have implemented a ring cavity to increase the circulating intensity of the two-photon excitation beam in rubidium. The resulting increase in gain for parametric four-wave mixing generates 1.9 \( \pm \) 0.3 mW of light at 420 nm, more than 50 times that possible without the cavity. In addition, the generated beam is shown to have an excellent spatial profile. The density and input power dependence of this process have been investigated, suggesting the process may be approaching saturation.

[1] R. M. Camacho, P. K. vudyasetu, and J. C. Howell, Nat. Photonics 3, 103 (2009).
[2] A. G. Radnaev, Y. O. Dudin, R. Zhao, H. H. Jen, S. D. Jenkins, A. Kuzmich, and T. A. B. Kennedy, Nat Phys 6, 894 (2010).
[3] Y.-H. Chen, F. Ripka, R. L"ow, and T. Pfau, Applied Physics B 122, 1 (2016).
[4] N. R. de Melo and S. S. Vianna, J. Opt. Soc. Am. B 31, 1735 (2014).
[5] E. Brekke, J. O. Day, and T. G. Walker, Phys. Rev. A 78, 063830 (2008).
[6] G. K. Gulati, B. Srivathsan, B. Chng, A. Cer"e, D. Matsukevich, and C. Kurtsiefer, Phys. Rev. A 90, 033819 (2014).
[7] E. E. Mikhailov, J. Evans, D. Budker, S. M. Rochester, and I. Novikova, Optical Engineering 53, 102709 (2014).
[8] P. Londero, V. Venkataraman, A. R. Bhagwat, A. D. Slepkov, and A. L. Gaeta, Phys. Rev. Lett. 103, 043602 (2009).
[9] B. Srivathsan, G. K. Gulati, B. Chng, G. Maslenikov, D. Matsukevich, and C. Kurtsiefer, Phys. Rev. Lett. 111, 123602 (2013).
[10] A. S. Zibrov, M. D. Lukin, L. Hollberg, and M. O. Scully, Phys. Rev. A 65, 053801 (2002).
[11] J. T. Schultz, S. Abend, D. D"oring, J. E. Debs, P. A. Altin, J. D. White, N. P. Robbins, and J. D. Close, Opt. Lett. 34, 2321 (2009).
[12] T. Meier, J. D. White, B. Sneets, M. Jeppesen, and R. E. Scholten, Opt. Lett. 31, 1002 (2006).
[13] A. M. Akulshin, R. J. McLean, A. I. Sedorov, and P. Han-