Cavity-enhanced frequency up-conversion in rubidium vapour

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We report the first use of a ring cavity to both enhance the output power and dramatically narrow the linewidth (< 1 MHz) of blue light generated by four wave mixing in a rubidium vapour cell. We find that the high output power available in our cavity-free system leads to power broadening of the generated blue light linewidth. Our ring cavity removes this limitation, allowing high output power and narrow linewidth to be achieved concurrently. As the cavity blue light is widely tunable over the \textsuperscript{85}Rb 5S_{1/2} F=3 \rightarrow 6P_{3/2} transition, this narrow linewidth light would be suitable for near-resonant rubidium studies including, for example, second-stage laser cooling.

Recent work on FWM in rubidium systems has show that transverse phase structure, for example orbital angular momentum (OAM), can be transferred between the pump and generated beams \textsuperscript{12, 13}. The ability to efficiently transfer OAM between different wavelengths may be important for future applications of structured light \textsuperscript{14}. Efficient FWM is not restricted to this particular system and various wavelengths can be generated by making use of different atomic states \textsuperscript{15–17} or different alkali metals \textsuperscript{18}. High conversion efficiencies have also been demonstrated in rubidium-filled hollow-core photonic crystal fibers \textsuperscript{19}.

In this letter we investigate the effect of adding a ring cavity, singly resonant with the generated blue light, to our rubidium vapour FWM system \textsuperscript{5}. We find that a low finesse cavity more than doubles the output power and greatly reduces the linewidth of the blue light produced. In previous single pass FWM experiments, for low output powers (around 10 µW), the linewidth of the coherent blue light has been reported to be \leq 3 MHz \textsuperscript{2, 20}. However, in our single pass setup, up to 340 µW of coherent emission can be generated. For these high output powers the linewidth of the blue light increases to around 33 MHz. This increase in linewidth is consistent with power broadening of the 420 nm transition due to the high peak blue light intensity, as discussed later in this work. Adding a ring cavity imposes stringent spectral coherence, allowing blue light to be generated with high output power (940 µW) as well as a narrow linewidth (\leq 1 MHz). FWM in a ring cavity using a purely near-infrared FWM scheme within rubidium has also recently been investigated \textsuperscript{21}.

Our experimental set-up and the relevant level scheme for 420 nm light generation in a rubidium vapour is shown in figure 1. The 780 nm and 776 nm pump beams undergo a single pass through a heated rubidium cell, exciting the two-photon resonance between the 5S_{1/2} ground state and the 5D_{3/2} excited state. This develops a population inversion on the 5D_{3/2} \rightarrow 6P_{3/2} transition which produces a 5.2 µm field via amplified spontaneous emission (ASE) \textsuperscript{2}. This initial ASE together with the pump lasers establishes three-photon coherence on the 5S_{1/2} \rightarrow 6P_{3/2} transition, which in turn allows for the coherent emission of 420 nm light via FWM. The ring cavity is designed to be singly resonant with this generated blue light, adding a strong constraint on the blue light frequency. The cavity also enhances the effective length of the "laser medium", thereby increasing FWM conversion efficiency. One would expect that the cavity also has an impact on the phase matching conditions for the FWM

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig1.png}
\caption{Schematic of the experimental setup. Abbreviations used are: PD (photodiode), PBS (polarising beam splitter), DM (dichroic mirror) and AL (achromatic lens, f = 200 mm). Dashed lines represent spectroscopy probe beams used to monitor the 780 nm and 776 nm detunings.}
\end{figure}
process, which we will investigate in the future.

The 780 nm and 776 nm pump beams are provided by two free running extended-cavity diode lasers (ECDLs). To ensure they are copropagating the pump beams are overlapped on a grating and then coupled into a polarisation maintaining single mode optical fibre. The combined 780 nm and 776 nm fibre output is then horizontally polarised before entering the cavity through a dichroic mirror. Two achromatic lenses form a 2f imaging system (f = 200 mm) that focuses the near-IR pump beam to a $e^{-2}$ radius of 52 $\mu$m in the centre of the heated rubidium cell. The cell is 25 mm long and contains $^{87}$Rb and $^{85}$Rb in their natural abundancies. The cell vapour temperature was determined to within $\pm 1^\circ$C using absorption spectroscopy of a weak (1 $\mu$W) collimated 780 nm probe beam [22].

FWM within the rubidium vapour produces horizontally polarised 420 nm light, copropagating with the pump beams. Light at 5.2 $\mu$m is also generated [17] but it is not observed in our setup as it is absorbed by the glass cell. In order for the cavity to be singly-resonant with the blue light we use a prism to separate the 420 nm light from the near-IR pump beam. The pump beam is then blocked and the blue light is fed back to the heated cell. A half waveplate and a polarising beam splitter (PBS) are used to couple light out of the cavity. The waveplate allows the amount of output coupling to be controlled. We have studied the effect of the cavity on FWM for 65% and 5% output coupling, which correspond to a cavity finesse of 3.5 and 12.8 respectively. The parasitic loss in our cavity is around 25%, the majority of this is due to loss at the PBS and the four 4% reflections at the cell.

Firstly, we will discuss the effect of the cavity on blue output power. We do this by comparing the output power as a function of 776 nm detuning for single pass FWM and with-cavity FWM, shown by the red and blue curves in figure 2. The output power was monitored using a photodiode at the cavity output and the single pass results were recorded simply by blocking the cavity after the PBS. When recording spectra the 780 nm laser was set to the detuning for maximum single pass blue power, as detailed in figure 2. The 776 nm detuning was determined by 780 nm and 776 nm two photon spectroscopy in the heated Rb cell and is given relative to the $^{85}$Rb 5P$_3/2$ F=4 $\rightarrow$ 5D$_5/2$ F=5 transition. The 780 nm detuning (relative to the $^{85}$Rb 5S$_{1/2}$ F=3 $\rightarrow$ 5P$_{3/2}$ F=4 transition) was determined by saturated absorption spectroscopy in a room temperature Rb cell.

For single pass FWM, as the 776 nm laser is scanned across the $^{85}$Rb 5P$_3/2$ $\rightarrow$ 5D$_5/2$ transition, there are two detunings for which blue light is produced, near $\Delta_{776} = -1.8$ GHz and $\Delta_{776} = 1.2$ GHz. These correspond to two-photon resonance with the 5S$_{1/2}$ F = 3 $\rightarrow$ 5D$_5/2$ and 5S$_{1/2}$ F = 2 $\rightarrow$ 5D$_5/2$ transitions respectively. In the cavity-enhanced results this same behaviour is observed but with the addition of large increases in blue output power when the 420 nm light, whose frequency scans with the 776 nm frequency, is resonant with the cavity.

Due to energy conservation, the frequency of the FWM fields must satisfy the condition $\omega_{780} + \omega_{776} = \omega_{5200} + \omega_{420}$, where $\omega_{780}$, $\omega_{776}$, $\omega_{5200}$ and $\omega_{420}$ are the frequency of the 780 nm, 776 nm, 5200 nm and 420 nm fields respectively. As a result, if the frequency of either of the pump lasers is changed then $\omega_{420}$ or $\omega_{5200}$ (or both) must

![FIG. 2. Blue output power as a function of 776 nm detuning for a single pass (P_{SP}, red lines) and with the cavity (P_{C}, blue lines). The right hand scale shows the blue intracavity power, P_{C}. Plots (a-f) correspond to the following conditions: (a, b) 130 °C, 1.6 mW 780 nm, 2.7 mW 776 nm; (c, d) 130 °C, 13 mW 780 nm, 23 mW 776 nm; (e, f) 90 °C, 13 mW 780 nm, 23 mW 776 nm. Cell temperatures of 130 °C and 90 °C correspond to vapour pressures of 0.12 Pa and 0.009 Pa respectively. The output coupling at the PBS was 65% for (a, c and e) and 5% in (b, d and f). Absolute frequency scales are accurate to $\pm 0.1$ GHz. The 780 nm detuning, chosen to maximise single pass blue power, was (a, b) 1.7 GHz; (c, d) 1.8 GHz; (e, f) 1.6 GHz. Representative values of the gain, G = P_{C}/P_{SP}, are shown, with the detuning each value was calculated at marked by a vertical dashed line.]
change accordingly. For the case of near resonant stepwise excitation of the $5S_{1/2} \rightarrow 5D_{5/2}$ transition it has been shown that the 420 nm frequency exactly mirrors changes in pump frequency. In our experiment we have measured (using a scanning Fabry-Perot interferometer) the change in $\omega_{420}$ due to a change in $\omega_{776}$ to be given by $\Delta \omega_{420} = 0.92(1) \Delta \omega_{776}$. This indicates that $\omega_{5200}$ and $\omega_{420}$ have mutual tuning consistent with relative Doppler shifts, as seen in Ref. [24], likely due to the detuning of our pump lasers from the $5P_{3/2}$ intermediate state ($< 2$ GHz). The mean separation of the observed cavity resonances in figure 2 is 198(2) MHz. This corresponds to a change in 420 nm frequency of 182(2) MHz, which is in strong agreement with the expected free spectral range (determined by the finesse) also plays a role. For 65% output coupling (left column) the passive cavity resonance width is 51 MHz, whilst for 5% output coupling (right column) it is reduced to 14.5 MHz. In figure 2(e) and (f) this decrease is enough to outweigh the increase in power broadening due to the increased intracavity power, and so the resonances in (f) are narrower. In figure 2(c) and (d) however the opposite is true, the change in power broadening is largest and consequently the resonances are broader for reduced output coupling.

However, it is clear that power broadening and the cavity finesse are not the only broadening mechanisms. For example, figure 2(a) has wider peaks than figure 2(e), for similar intracavity power, suggesting that collision broadening may have some contribution. Moreover, in figure 2(b) the cavity resonances near the $F = 2$ two-photon transition (positive detuning) are narrower and give much higher gain than those near the $F = 3$ transition (negative detuning). A theoretical model of the

![FIG. 3. Beat note between the FWM blue light and a 420 nm ECDL. The FWM cavity conditions were: 65% output coupling, 13 mW 780 nm, 23 mW 776 nm and cell temperature (a, b) 130°C and (c, d) 90°C. The 780 nm and 776 nm detunings were within 0.1 GHz of their optimal detunings for single pass FWM. Plots (a) and (c) compare the beat note signal (BNS) for a single-pass (red, BNSp) and with the cavity (blue, BNSc). $\Delta \omega_{420}$ gives the detuning of the FWM blue light from the $^{85}$Rb $5S_{1/2} \rightarrow 5P_{3/2}$ transition, to within ±25 MHz. In (a) and (c) the width of the cavity-enhanced BNS is limited by the signal analyser sweep rate; (b) and (d) show the normalised BNSc (nBNSc) over a smaller scan range on a relative frequency scale. Image (d) shows only the larger of the two peaks in (e). The dashed lines are Lorentzian fits with FWHM (a) 33 MHz; (b) 0.7 MHz; (c) 11 MHz and (d) 0.7 MHz.](image-url)
tem will undoubtedly provide insight into this behaviour. We have also demonstrated that the cavity significantly decreases the linewidth of the generated blue light. We obtained the linewidth by beating the FWM blue beam against a 420 nm ECDL (Newport Vantage tunable diode laser) and measured the resulting beat note using a spectrum analyser. The frequency of the 420 nm ECDL was monitored using saturated absorption spectroscopy, allowing the absolute frequency of the blue FWM light to be determined as well as the linewidth. Figure 3 shows the result of the beat note measurement for single pass and cavity-enhanced blue light generation, taken at both 90°C and 130°C. The 780 nm and 776 nm pump powers were 13 mW and 23 mW respectively. In the following we will first briefly discuss the beat note obtained for blue light generated via single pass FWM, and then go on to discuss the cavity-enhanced case.

The single pass beat note, both at 90°C and 130°C, is composed of more than one subpeak. Similar substructure has been observed previously in [2] where it was explained by the 6P3/2 hyperfine splitting of 10, 20 and 40 MHz between the F′ = 1, 2, 3, 4 levels. However, in our measurement the width of the subpeaks makes it difficult to determine if the substructure we observe is from the same source. Fitting to one of the subpeaks of the observed beat note signal gives the beat note linewidth to be 11 MHz (33 MHz) at 90°C (130°C). We attribute this difference in FWHM to power broadening of the 420 nm transition, as collision broadening of the 420 nm transition is negligible. Based on the single pass blue power and the e−2 radius of the blue light in the rubidium cell (46µm), we calculate the power broadened width of the 420 nm transition to be 4 MHz (41 MHz) at 90°C (130°C) [25].

For a single pass, we find that maximal blue light is generated slightly red detuned from the 420 nm transition, as shown in figure 3 (a) and (c). These detunings are within a Doppler width of the 420 nm resonance and so are in agreement with previous work [23]. In addition, we find that the blue light can be tuned easily to frequencies either side of the transition, with a FWHM tuning range of 920(25) MHz and 770(25) MHz at 130°C and 90°C respectively.

Figure 3 (b) and (d) show the beat note for the cavity-enhanced blue light. At both 130°C and 90°C the linewidth is dramatically narrowed to ≤1 MHz FWHM. For the 130°C cell the beat note produced is a single sharp peak of FWHM 0.7 MHz. At 90°C the with-cavity light has a similar linewidth but there is an additional secondary peak in the beat note signal. As this beat note is for the cavity-enhanced case this secondary peak is likely due to a cavity mode, rather than due to hyperfine processes, indeed measurements of the beam profile at the cavity output indicate that it may be due to higher order transverse modes.

In conclusion, we have demonstrated the first use of a ring cavity to both enhance the power output and dramatically narrow the linewidth of blue light generated via FWM in a rubidium vapour cell. For a cell temperature of 130°C the resulting output power is nearly 1 mW (nearly three times the output power of the cavity-free case) and the linewidth drops from a power broadened 33 MHz to less than 1 MHz. Furthermore, the blue light is generated with a frequency close to the 85Rb 5S1/2 → 6P3/2 transition and is tuneable over a FWHM range of almost 1 GHz. The increased output power, narrow linewidth and large tuning range could make this FWM in a ring cavity system a valuable light source for efficient 85Rb Bose-Einstein condensate production [26]. In addition, if the input laser powers were increased or the large parasitic losses present in our cavity minimised, for example by using an anti-reflection coated or Brewster cell, then even larger output powers would be possible. The datasets used in this Letter are available via Ref. 27.

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