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Cover Picture: A Rubidium vapour cell illuminated with infrared light at 780nm and 776nm wavelength, and producing blue up-converted coherent light, as seen on the white card. See article by Scholten et al. in this issue.
Coherent blue laser beam production in a rubidium vapour cell

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Introduction

A blue laser beam at 420 nm has been produced via coherent two-step excitation using 780 and 776 nm lasers and a rubidium vapour cell, as recently described by Ref. [1]. The process demonstrates efficient frequency up-conversion, producing 40 µW of blue output with pump beam powers of 15 mW each, orders-of-magnitude greater efficiency than traditional up-conversion using nonlinear crystals. The process has been explored as a function of pump laser frequencies, and the blue coherence has been investigated through double-slit interference. In addition to the details of the experimental investigation, a semiclassical model of the system is presented. The model shows that coherent excitation of two transitions induces a transparency on the 420 nm transition, which permits gain without inversion.

Setup

In our experiments, two co-propagating infrared laser beams at 780 nm and 776 nm are directed through a Rb vapour cell with natural isotopic abundance of $^{85}$Rb and $^{87}$Rb (Fig. 1). The power in each beam was 15 mW, focused to a beam waist of approximately 0.4 mm ($1/e^2$ diameter). The cell was heated to 280°C. The infrared lasers were independently tunable. Strong blue fluorescence was observed, and a coherent beam at 420 nm (measured with a 15 cm monochromator) propagating in the forward direction, i.e. co-propagating with the infrared lasers.

![Figure 1: Experimental configuration.](image)

Fluorescence from the Rb system is understood by considering the simplified level-scheme for Rb shown in figure 2. The two pump lasers are tuned to the $^5S_{1/2} - ^5P_{3/2} (|1\rangle - |2\rangle)$ transition at 780 nm, and to the $^5P_{3/2} - ^5D_{5/2} (|2\rangle - |3\rangle)$ at 776 nm. When the frequency sum for the two lasers matches the two-photon resonance, a large population is created in excited state $|3\rangle$, and a large coherence $|p_{13}|$ between the ground and excited states. The long-lived $^5D_{3/2}$ state
(\tau_3 = 240\,\text{ns}) can decay via spontaneous emission to the 6P_{3/2} (|3\rangle \rightarrow |4\rangle), which then decays back to the ground state |1\rangle emitting 420 nm fluorescence.

Numerous novel effects have been seen with this system, including enhanced index of refraction, slow light, Electromagnetically Induced Transparency (EIT), and counterintuitive results such as Lasing Without Inversion (LWI) [2]. Ref. [1] first observed production of a coherent collimated blue beam, with power up to 12\mu W. We confirm their results and demonstrate the spatial and temporal coherence, and have achieved more than three times their output power.

**Experimental results**

The previous maximum output of 12\mu W was found for a detuning of the 780 nm laser of 120 MHz above resonance [1]. We have also found significant (2\mu W) output at this detuning, but we find dramatically greater output power (40\mu W) for a detuning of the 780 nm laser by about 1 GHz above resonance.

The output was also measured as a function of the 776 nm laser frequency (Fig. 3). These traces only show the 420 nm beam output for a detuning range of less than a few hundred megahertz. The structure in this tuning range, as well as structure over a larger range including the region of maximum output power, has not been explained to date. Previous studies have measured the spectral width of the blue beam to be \leq 2 MHz, but measurements of the degree of coherence have otherwise not been made. We have shown that the beam has a strong degree of coherence, by producing a Young’s double slit pattern (Fig. 4). The image was taken with slits of width 0.04 mm and separation 0.25 mm. The high fringe contrast demonstrates strong coherence. Future experiments will measure the coherence in detail using Wigner phase-space tomography.

**Theoretical modelling**

We have modelled the system with a standard semi-classical treatment, using the density matrix \rho to describe the macroscopic atomic populations and coherences. The time evolution of the density matrix is given by:

\[
\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar} [H, \rho]
\]  

(1)
Figure 3: 420 nm output power as a function of the 780 nm laser frequency, for various detunings of the 776 nm laser. The saturated absorption curve provides a frequency reference for the 780 nm laser. The 780 and 776 nm laser beams were also counter-propagated through a separate vapour cell; the fluorescence peak occurs when the combined detuning is zero.

Figure 4: Intensity image of double-slit interference of the blue light, with slits of 0.04 mm width and 0.25 mm separation. A single line profile across the fringes is also shown. No attempt has been made to subtract background.

The Hamiltonian in the interaction picture describing the four levels and coupling light fields is, in the rotating wave approximation,

\[
H = \frac{\hbar}{2} \begin{pmatrix}
0 & \Omega_{21} & 0 & \Omega_{41} \\
\Omega_{21} & 2\Delta_{21} & \Omega_{32} & 0 \\
0 & \Omega_{32} & 0 & 2(\Delta_{21} + \Delta_{32}) \\
\Omega_{41} & 0 & \Omega_{34} & 0
\end{pmatrix}
\]  

(2)
where the $\Omega_{ij}$ are the Rabi frequencies and $\Delta_{ij}$ are the relative detunings. The Rabi frequencies $\Omega_{34}$ and $\Omega_{41}$ are for the spontaneously generated 5 $\mu$m and 420 nm fields. Decay terms are added phenomenologically [3]. For the diagonal elements the equations are:

$$\frac{\partial \rho_{ii}}{\partial t} = -\frac{i}{\hbar} [H, \rho_{ii}] - \sum_j \Gamma_{ij} \rho_{ii} + \sum_k \Gamma_{ik} \rho_{kk}$$  \hspace{1cm} (3)

in which $\Gamma_{ij}$ is the decay rate from $|i\rangle$ to $|j\rangle$. For the the off-diagonal terms the equations are:

$$\frac{\partial \rho_{ij}}{\partial t} = -\frac{i}{\hbar} [H, \rho_{ij}] - \frac{1}{2} \sum_k (\Gamma_{jk} + \Gamma_{kj}) \rho_{ij}.$$  \hspace{1cm} (4)

This system of coupled first order differential equations can be solved by the method of eigenvector expansion, showing that a unique steady state exists. The fields were modelled through Maxwell’s equation:

$$\frac{\partial}{\partial t} E = -\frac{\omega}{2\varepsilon_0 c} Im \rho P$$  \hspace{1cm} (5)

where $E$ and $P$ are the slowly varying amplitudes for the electric field and polarisation, respectively. The steady state solution was used to solve Maxwell’s equations for the evolution of the fields as they propagate through the cell. A weak seed field on the 5 $\mu$m transition was included, physically equivalent to some initial spontaneous emission.

![Graph showing gain and absorption](image)

**Figure 5:** On-resonance simulation results showing gain in the 420 nm transition, and the different field strengths along the cell, in terms of their Rabi frequencies.

Figure 5 shows results from the simulation. The imaginary part of $\rho_{14}$ (proportional to gain or absorption of the 420 nm light) becomes positive when the two infrared lasers are on resonance. The four field strengths are shown in terms of their Rabi frequencies, as a function of propagation distance through the cell.

Our results demonstrate efficient frequency up-conversion using low-power laser beams in a vapour cell. The model qualitatively predicts the behaviour of the system, and in particular inversionless gain at the appropriate laser detunings. We are now extending the model to include hyperfine structure and the atomic velocity distribution, such that quantitative predictions of output power can be made.

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