Towards multi-photon Raman scattering
with higher excited levels of rubidium atoms in a warm ensemble

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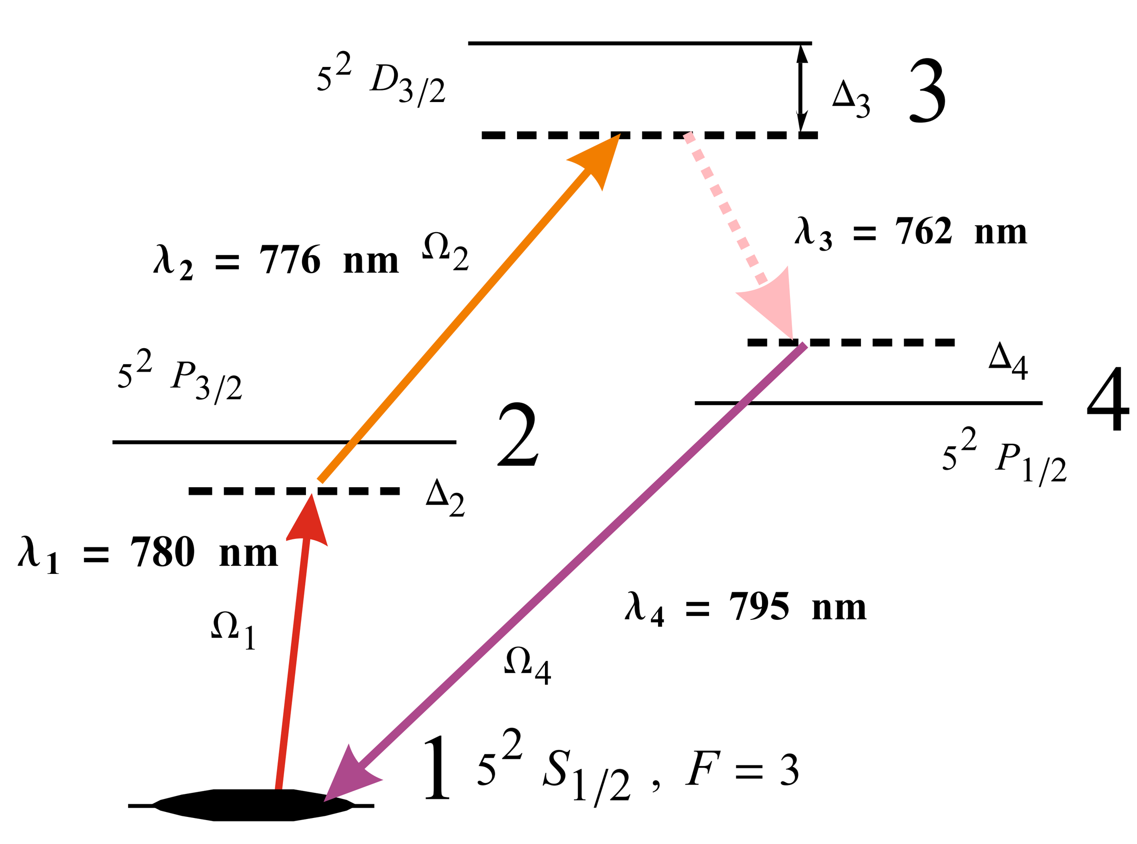
I. INTRODUCTION

Warm rubidium vapors constitute a versatile medium for quantum engineering with light and atoms. Optical transitions to the lowest excited levels, the D1 and D2 lines, are widely used, enabling the quantum memory for light based on Raman scattering [1].

On the other hand, the usage of higher excited levels is not so common. Here we present a scheme for non-linear frequency conversion using the so-called diamond configuration of atomic levels [2,3]. We study the spectral properties of four wave mixing signal in the presence of Doppler broadening, both experimentally and theoretically.

Finally, we demonstrate a quantum memory scheme that would join the possibilities given by the Raman scattering and the diamond configuration

II. CLOSED DIAMOND CONFIGURATION



The diamond configuration consists of four atomic levels coupled by light, forming a closed loop transition. We use three excited levels of rubidium and the ground state. Three coupling lasers at 780 nm (1-2 transition), 776 nm (2-3 transition) and 795 nm (4-1 transition) result in emission of 762 nm light (3-4 transition).

We define the detunings Δ as complex variables: the real part is the actual laser detuning, while the imaginary part is the relaxation rate Γ.

We consider a single atom and calculate the lowest non-vanishing order of the perturbation series for atomic coherence resulting in emission from the 3-4 transition in terms of Rabi frequencies.

$$\rho_{34} = \frac{\rho_{11}\,\Omega_1\,\Omega_2\,\Omega_4^*}{8\,\Delta_1\,\Delta_2\,\Delta_4^*}$$

In order to include the Doppler broadening we average the above expression over all velocity classes.

$$\rho_{34} = \sqrt{\frac{m}{2\pi k T}}\int_{-\infty}^{\infty}\frac{\rho_{11}\,\Omega_1\,\Omega_2\,\Omega_4^*}{8\,(\Delta_1+v/\lambda_1)\,(\Delta_2+v/\lambda_1+v/\lambda_2)\,(\Delta_4^*+v/\lambda_4)}\exp\left(-\frac{m v^2}{2kT}\right)dv$$

The integration can be carried out analytically, if we first perform the partial fractions decomposition in terms of velocity.

$$\rho_{34} = \sqrt{\frac{m}{2\pi k T}}\int_{-\infty}^{\infty}\rho_{11}\left(\frac{\lambda_2\,\lambda_4\,\lambda_1\,\Omega_1\,\Omega_2\,\Omega_4^*}{8\,(\Delta_1\lambda_1+\Delta_1\lambda_2-\Delta_2\lambda_2)\,(\Delta_1\lambda_1-\lambda_4(\Delta_4)^*)\,(\Delta_1\lambda_1+v)} - \frac{\lambda_1^2\,\lambda_2\,\lambda_4\,\Omega_1\,\Omega_2\,\Omega_4^*}{8\,(\Delta_1\lambda_1-\lambda_4\Delta_4^*)\,(\lambda_4\lambda_2\Delta_4^*+\lambda_1\lambda_4\Delta_4^*-\Delta_2\lambda_1\lambda_2)\,(\lambda_4\Delta_4^*+v)} - \frac{\lambda_1\,\lambda_2\,(\lambda_1+\lambda_2)^2\,\lambda_4\,\Omega_1\,\Omega_2\,\Omega_4^*}{8\,(\Delta_1\lambda_1+\Delta_1\lambda_2-\Delta_2\lambda_2)\,(-\lambda_4\lambda_2\Delta_4^*-\lambda_1\lambda_4\Delta_4^*+\Delta_2\lambda_1\lambda_2)\,(\Delta_2\lambda_1\lambda_2+(\lambda_1+\lambda_2)v)}\right)\exp\left(-\frac{m v^2}{2kT}\right)dv$$

Each component being of the following form is integrated separately, and the result is expressed in terms of the Faddeeva special function w(z).

$$\sqrt{\frac{m}{2\pi k T}}\int_{-\infty}^{\infty}\frac{A\exp\left(-\frac{m v^2}{2kT}\right)}{a v+b}\,dv = \frac{A}{a}\,i\sqrt{\frac{\pi m}{2kT}}\,w\left(-\frac{b}{a}\sqrt{\frac{m}{2kT}}\right)$$

The last step is to include rich level structure of the real atom, that is hyperfine splitting and degeneracy. We consider all possible closed diamond configurations (beginning and ending with the same level) and add their contributions.

$$\rho_{34} = \sum_{\substack{m_{F_1},F_2,m_{F_2},\\ F_3,m_{F_3},F_4,m_{F_4}}} \rho_{34}\big((F_1,m_{F_1})\to(F_2,m_{F_2})\to(F_3,m_{F_3})\to(F_4,m_{F_4})\to(F_1,m_{F_1})\big)$$

Final light intensity is proportional to the absolute value squared of the coherence.

$$|\Omega_3|^2 \propto |\rho_{34}|^2$$

III. EXPERIMENTAL

Focal plane image demonstrates the phase matching condition.

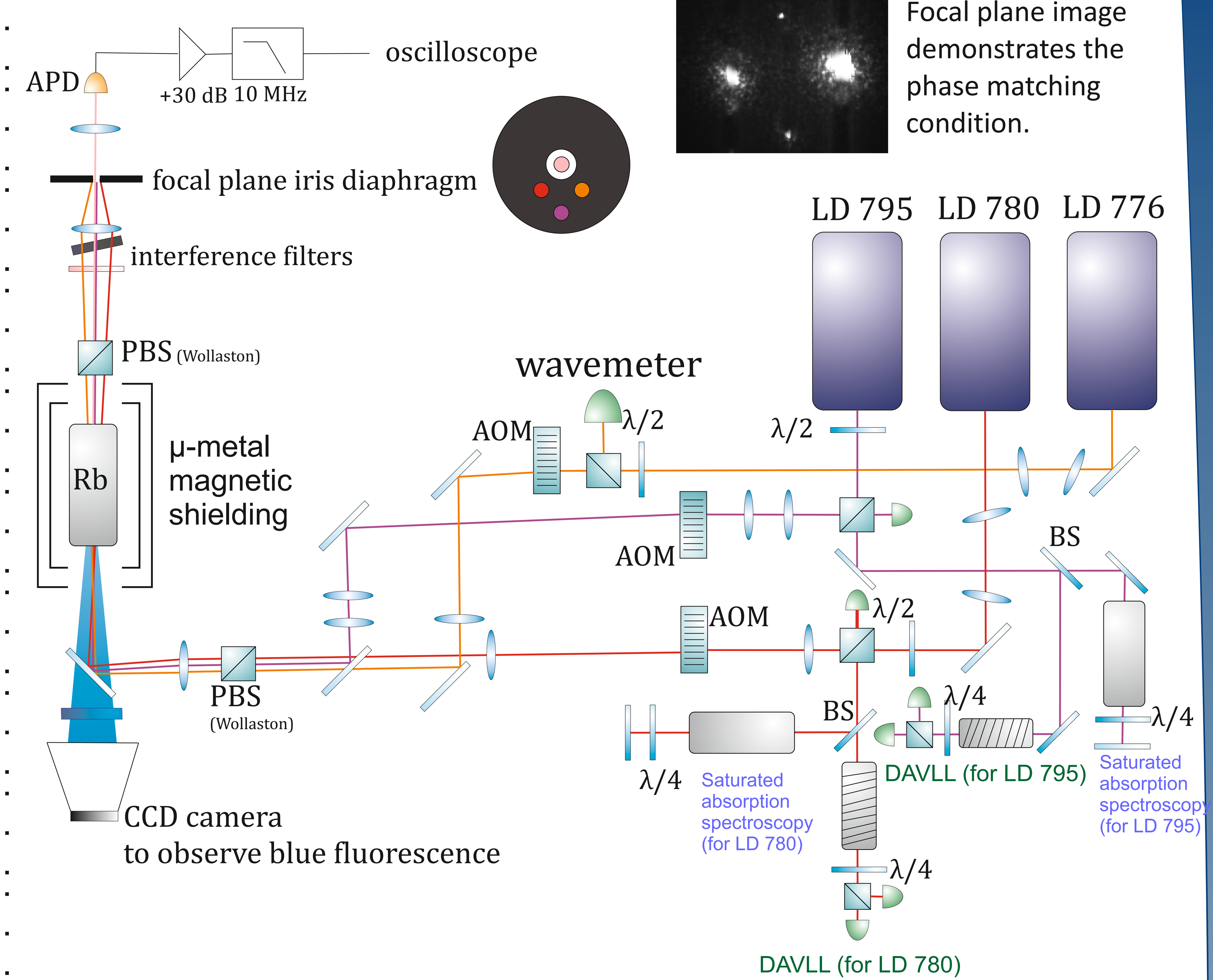
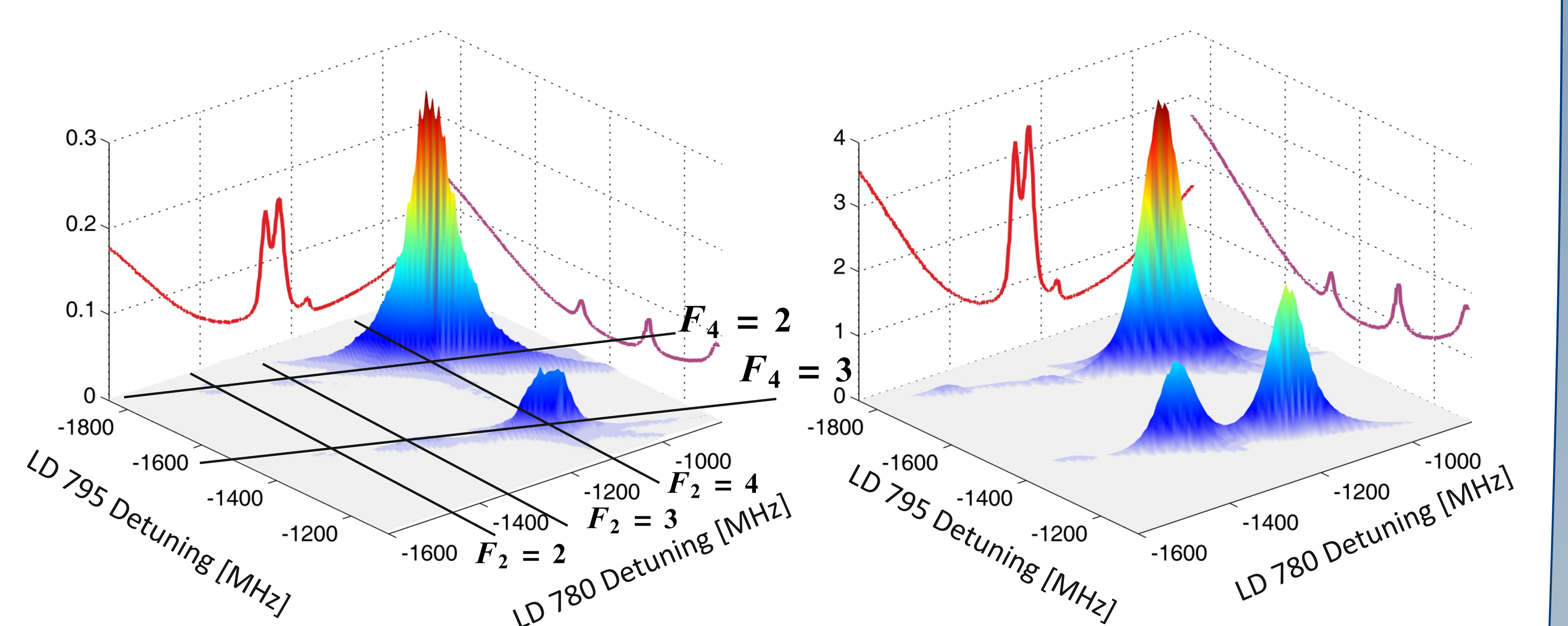
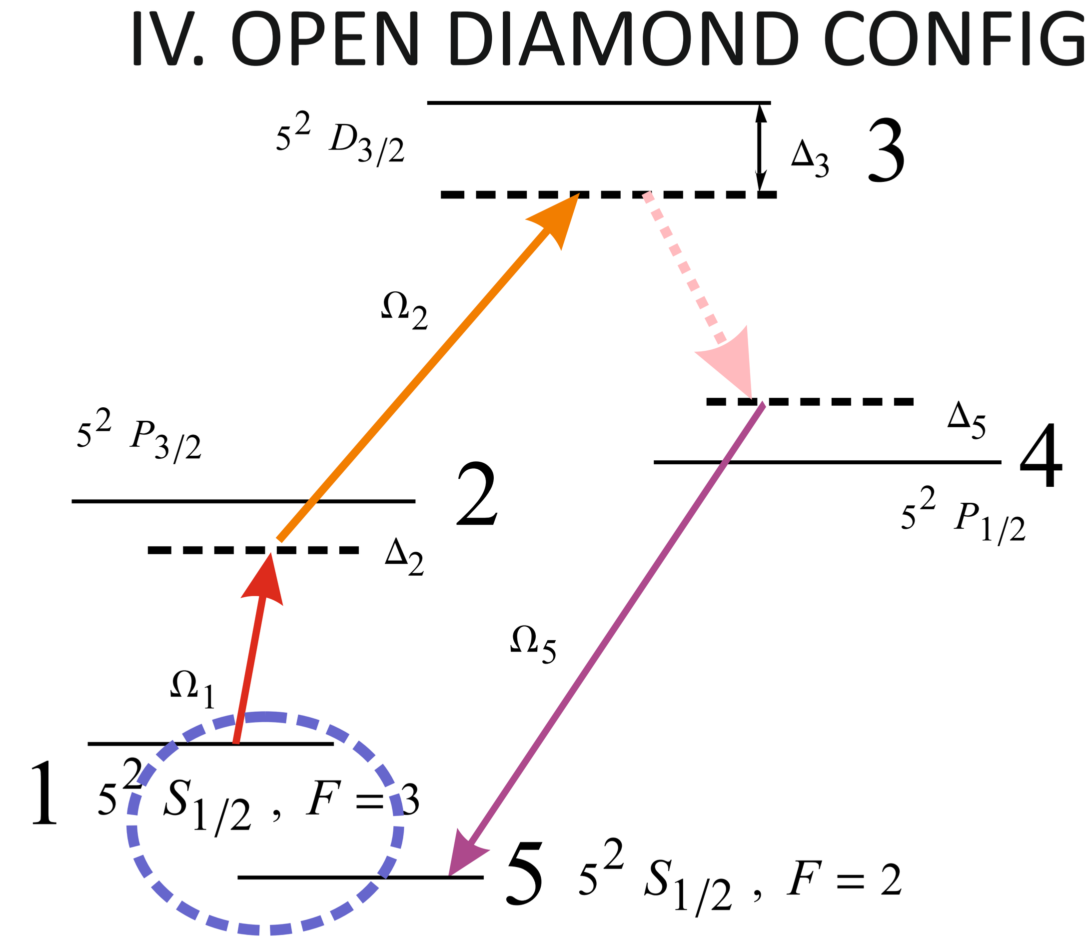


Figure demonstrates the experimental setup used to generate light at 762 nm via four wave mixing. Beams from three lasers (LD 780, LD 776, LD 795) intersect at a small angle (8 mrad) inside magnetically shielded hot (100 deg. C) rubidium cell. Generated 762 nm light is separated both spectrally (using interference filters) and spatially from the other three beams. From approximately 30 mW at each of the incident beams we obtain at most 100 nW of 762 nm light.
(AOM - acousto-optical modulator, λ/2 - half wave plate, λ/4 - quarter wave plate, APD - avalanche photodiode, (P)BS - (polarizing) beamsplitter, LD - laser diode)



Experimental (left) and theoretical (right) spectrum of four wave mixing. Reference curves are measured using saturated absorption spectroscopy.

IV. OPEN DIAMOND CONFIGURATION



$$\rho_{34} = \frac{\rho_{51}\,\Omega_1\,\Omega_2\,\Omega_5^*}{8\,\Delta_1\,\Delta_2\,\Delta_5^*}$$

A new scheme of atomic quantum memory for light:
reading - applying only coupling lasers to probe the ground state coherence
writing - applying light at 762 nm to create ground state coherence

Main advantage over Λ-configuration:
scattered photons have a completely different wavelength - ease of spectral separation

References:
[1] Chrapkiewicz, R., & Wasilewski, W. (2012). Generation and delayed retrieval of spatially multimode Raman scattering in warm rubidium vapors. Optics Express, 20(28), 29540.
[2] Willis, R., Becerra, F., Orozco, L., & Rolston, S. (2009). Four-wave mixing in the diamond configuration in an atomic vapor. Physical Review A, 79(3), 033814.
[3] Chanelière, T., Matsukevich, D., Jenkins, S., Kennedy, T., Chapman, M., & Kuzmich, A. (2006). Quantum Telecommunication Based on Atomic Cascade Transitions. Physical Review Letters, 96(9), 093604.

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