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Highly selective four-wave mixing of low-intensity radiation in a degenerate two-level atomic system

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Abstract. Quasi-degenerate four-wave mixing (FWM) of low-intensity radiation (with an intensity less than 1 mW cm^{-2}) was observed for the $5S_{1/2}(F=2)-5P_{3/2}$ $(F'=3)$ transition in an optically transparent ^{87}Rb vapour under conditions of electromagnetically induced absorption. The efficiency of frequency conversion was no less than 1% with respect to the intensity of pump waves. Nonlinear FWM is highly selective relative to the frequency detuning of pump waves (the FWM full width at half maximum was less than 50 kHz).

Media and excitation schemes that ensure the maximum nonlinearity with minimum intensity of pump radi-ation are of considerable interest in the context of nondemolition measurements and optical data processing. Coherent population trapping and electromagnetically induced transparency (EIT) are known to improve the efficiency of four-wave mixing (FWM) in an absorbing medium [1].

As has theoretically been demonstrated recently (see Ref. [2] and references therein), efficient nonlinear processes can be observed with radiation powers of the order of 1 μW under conditions of total EIT, when the group velocity of light radically is lowered ($V_g/c \leqslant 10^{-6}$). However, the EIT effect is not necessary for ensuring a high nonlinearity. In particular, a high nonlinear susceptibility $\chi^{(3)}$ was obtained with the pump intensity $I \approx 0.1$ mW cm^{-2} under conditions of induced absorption observed for a degenerate two-level transition (DTLT) in a Rb vapour [3 – 5]. The pump intensities in these studies were an order of magnitude lower than the saturation intensity for the optical transition under investigation (the nonlinear Kerr coefficient was $n_2 = 8 \times 10^{-3}$ cm W^{-2} [6]). The specific features of FWM for different polarisations of resonant radiation in the presence of a magnetic field were considered with the use of a DTLT model developed in Ref. [7].

The purpose of this study is to demonstrate experimentally the nonlinear mixing of low-intensity radiation invol-ving DTLTs under conditions of induced transparency and absorption. Our experiments were performed for the $\lambda = 780$ nm D_2 absorption line in ^{87}Rb vapour.

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Cyclic, or closed, $F=2-F'=3$ and $F=1-F'=0$ optical transitions (F and F' are the total angular momenta of the ground and excited states), which do not redistribute populations over the hyperfine structure sublevels of the ground state, can be satisfactorily described in terms of the DTLT model in the absence of a magnetic field.

An optical diagram of our experiments is shown in Fig. 1a. A 5 cm sealed glass cell contained a room-temperature ^{87}Rb vapour. The external magnetic field in the cell was attenuated down to 10 mG with a μ-metal screen. An external-cavity injection laser served as a source of resonant radiation with a radiation bandwidth not exceeding 1 MHz. Sub-Doppler saturated-absorption resonances observed in an auxiliary cell were used as reference lines in electronic stabilisation of the laser frequency.

Two mutually coherent waves with a variable frequency detuning ($\delta = \omega_2 - \omega_1$) were produced by acoustooptical modulators (AOMs) controlled by oscillators with fixed (200 MHz in the case of AOM1) and tunable (200±5 MHz for AOM2) frequencies. The maximum intensities of pump waves with frequencies ω_1 and ω_2 at the input of the cell were 0.5 and 0.03 mW cm^{-2}, respectively.

The heterodyning technique was used to detect new waves arising due to FWM. The reference wave with a frequency ω_0 ($\omega_0 - \omega_1 = \varDelta = 2\pi \times 80$ MHz) was produced by AOM3. All three waves were linearly polarised, and the polarisation vector of the highest intensity wave with the frequency ω_1 was

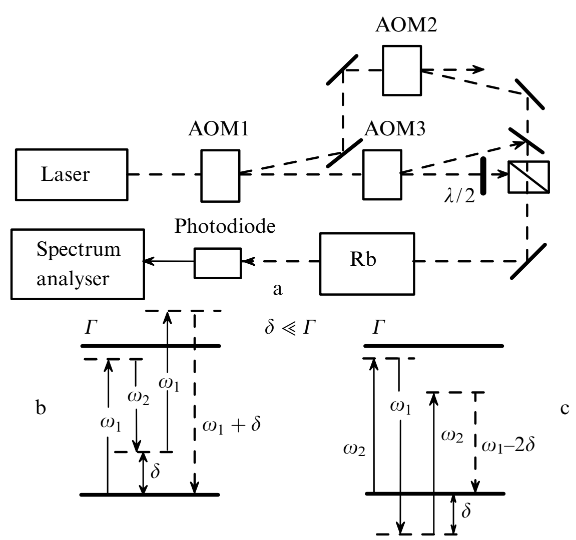

Figure 1. Optical diagram of experiments (a) and (b, c) schemes of nonlinear mixing with frequencies ω_1 and ω_2 involving a degenerate two-level transition (Γ is the natural line width).

orthogonal to the polarisation vectors of two other waves. Propagation of these waves, brought into a monodirectional beam, through a 50 cm single-mode optical fibre made the pumping scheme perfectly collinear. Some depolarisation of radiation in the fibre allowed us to detect beats of the reference wave with the wave at frequency ω_1.

In the classical scheme of nondegenerate phase-matched FWM, when the condition $\boldsymbol{k}_4 = \boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}_3$ is satisfied, where $\boldsymbol{k}_i$ are the wave vectors, nonlinear wave mixing gives rise to a new wave with a frequency $\omega_4 = \omega_1 + \omega_2 - \omega_3$ and an amplitude $E_4 \propto \chi^{(3)} E_1 E_2 E_3$. When a DTLT coherence is excited with copropagating waves with amplitudes E_1 and E_2 and frequencies ω_1 and ω_2, the absorption of two photons from one wave and stimulated emission of a photon at the frequency of the second wave give rise to the waves with frequencies $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$ (Figs 1b, 1c) and amplitudes $\chi^{(3)} E_1^2 E_2$ and $\chi^{(3)} E_2^2 E_1$, respectively.

Thus, two new components arise in the beat spectrum of the reference wave (with an amplitude E_0) propagating through a Rb vapour simultaneously with two pump waves (Fig. 2). The fact that the amplitude of the beat signal at the frequency $2\omega_1 - \omega_2$ is higher than the amplitude of the signal at the frequency $2\omega_2 - \omega_1$ is due to the difference in pump wave intensities I_1 and I_2. The beat signals at these frequencies are proportional to $E_0 I_1 \sqrt{I_2}$ and $E_0 I_2 \sqrt{I_1}$, respec-tively. These dependences were also observed in experiments.

The maximum efficiency of FWM in an optically rarefied resonant medium (with a linear absorption of less than 40%) under conditions of electromagnetically induced absorption with the laser frequency tuned to the $5S_{1/2}(F=2) - 5P_{3/2}$ $(F'=3)$ transition of ^{87}Rb (the nuclear spin is $I = 3/2$) was close to 2% of the intensity of the strong wave. We should emphasise that, in the EIT regime, when the laser frequency was tuned to another hyperfine sublevel of the ground state with $F = 1$, the FWM signal was three times weaker.

Wave mixing involving DTLTs with low-intensity radiation is characterised by a sufficiently high intensity because the frequencies of new waves are exactly resonant to the optical transition. This is the main difference between the scheme employed in this paper and asymmetric Λ schemes [8], where the frequency detuning of new waves is equal to the hyperfine splitting of the ground state, considerably exceeding the inhomogeneous line width ($\Delta_{\rm hf} > \Delta\nu_{\rm D}$).

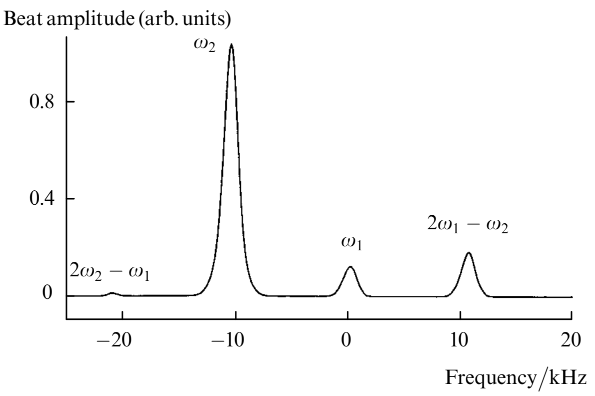

Figure 2. The spectrum of beats of the reference wave with pump waves with frequencies ω_1 and ω_2 and two waves emerging from FWM under conditions of electromagnetically induced absorption in a ^{87}Rb vapour. The detuning of the pump waves with frequencies ω_1 and ω_2 and intensities of 0.5 and 0.03 mW cm^{-2} was equal to 10 kHz.

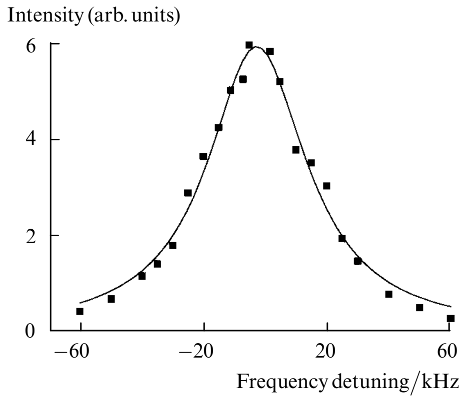

Figure 3. The intensity of the FWM wave (at the frequency $2\omega_1 - \omega_2$) due to the D_2 line in a coherent Rb vapour as a function of the frequency detuning of the pump waves ($\delta = \omega_2 - \omega_1$): (dots) experimental data and (solid line) approximation with a Lorentzian contour.

Fig. 3 presents the intensity of the FWM signal as a function of the frequency detuning of two pump waves. The full width at half maximum of the FWM signal contour is 44 kHz, which is much less than the homogeneous width of the optical transition ($\Gamma/2\pi \approx 6$ MHz). This result demonstrates the high selectivity of the nonlinear process considered.

Thus we demonstrated for the first time that quantum interference, which may be either destructive or constructive for different atomic degenerate two-level transitions, increasing either transparency or absorption of the medium, enhances considerably the nonlinearity of the medium. This effect allows efficient quasi-degenerate wave mixing to be implemented with very low intensities of pump radiation. The generation of radiation with the level of amplitude noise lower than the quantum limit (squeezed light) seems to be one of the most interesting applications of the simple scheme of nonlinear mixing proposed in this paper.

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