J. At. Mol. Sci.
doi: 10.4208/jams.060310.072010a

Vol. **1**, No. 4, pp. 337-343
November 2010

# Dependence of four-wave mixing line-shape on micrometric atomic vapor thickness

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Received 3 June 2010; Accepted (in revised version) 20 July 2010
Published online 2 August 2010

**Abstract.** We theoretically examine thickness and wavelength dependence line-shape of four-wave-mixing (FWM) spectroscopy in micrometric thin atomic vapors whose thickness $L$ is assumed to be 10,30,50,80 and 100 $\mu$m respectively. It is found that a narrow centre (Dicke-narrowing) persists for all cases, while wings are broadened as the thickness of the vapor increases or the pump wavelength decreases comparing to the probe wavelength. This type of spectrum is due to the modified velocity distribution and polarization interference from different ensemble of atoms in a confined situation.

**PACS**: 42.50.Gy, 32.80.Qk, 42.65.-k

**Key words**: four-wave mixing, micrometric atomic vapor, Dicke-narrowing, polarization interference

## 1 Introduction

Width narrowed spectral lines (Dicke-narrowing) in thin vapor cells are firstly observed in optical region by Briaudeau et al. [1]. This narrowing structure spectrum is due to the enhanced contribution of slow atoms in the thin vapor, where the duration of the atom-laser interaction governed by wall-to-wall trajectories is anisotropic [2–4]. The contribution of atoms with slow normal velocity is enhanced thanks to their longer interaction time with the laser field [2–4]. Under normal incidence irradiation, the resonance of these atoms, flying nearly parallel to the wall and yielding a stronger contribution to the signal, appears to be insensitive to the Doppler shift [2–4].

Several absorption emission cycles can take place due to the fact that the longer atom-light interaction time in a micrometric vapor compared to the excited state decay [5]. However, the optical pumping efficiency is strongly dependent on the atomic velocity

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and only the slowest atoms may approach a steady state [5]. Thus very narrow spectra can be achieved due to atom-wall collision in such a confined atomic system [5].

Many authors have demonstrated that, the cell's thickness is the main factor which influences the shape and the magnitude of the spectra of a thin vapor column both in theory and experiment [2–4, 6]. This modification can be extended to electromagnetically induced transparency (EIT) dips [7, 8] and FWM spectroscopy [7]. In this paper, we predict FWM lines for five type vapors with a thickness of 10,30,50,80 and 100 $\mu$m respectively. Potential applications of FWM process, e.g., the measurement of atomic exited state lifetimes [9], coherent anti-stokes Raman spectroscopy (CARS) [10], generation of coherent sources in the ultraviolet (UV) and infrared radiation (IR) [11–13] and femtosecond pulse generation [14], and generation of correlated photon pairs [15, 16] can be extended to micrometric thin vapors.

We consider three typical cases of wavelength configurations [17] corresponding to different type of polarization interference [18–20], where the cases for the probe wavelength is less, equal and greater than the pump wavelength are respectively termed as mismatched case I, matched case, and mismatched case II [17, 20]. A narrow line centre persists for all lines of micrometric thin vapors, while wings are broadened as the thickness of the vapor increases or the pump wavelength decreases comparing to the probe wavelength. Very narrowing FWM lines can be achieved in experiment by using proper thin vapor cells. This type of spectrum can be demonstrated by the transient effect of confined atoms and polarization interference from different ensemble of atoms in thin vapors.

## 2 Theoretical model

We consider a phase-conjugated beam configuration (Fig. 1(a)) applied to a cascade three-level atomic system (Fig. 1(b)), where $|0\rangle$, $|1\rangle$ and $|2\rangle$ are the ground, the intermediate and the excited states respectively. Beam 1 represents the probe field $\varepsilon_1$, beams 2 and 3 propagating with a small angle difference (about 0.5°) consist of pump fields $\varepsilon_2$ and $\varepsilon_2{}'$ respectively. Rabi frequencies $g_1$, $g_2$ and $g_2{}'$ are respectively defined as $g_1=\mu_{10}\varepsilon_1/\hbar$, $g_2=\mu_{21}\varepsilon_2/\hbar$ and $g_2{}'=\mu_{21}\varepsilon_2{}'/\hbar$. The FWM signal can be generated and propagates almost opposite to the beam 3 if the phase-matching condition $k_F=k_1+k_2+k_2{}'$ is satisfied, where $k_i(k_i{}')$ is the wave vector of the field $\varepsilon_i(\varepsilon_i{}')$ ($i=1$, 2).

We define

$$\Lambda_{10}=\Gamma_{10}+i(k_1\nu+\Delta_1), \quad \Lambda_{20}=\Gamma_{20}+i(k_1\nu+k_2\nu+\Delta_1+\Delta_2)$$

as the Doppler-shifted detunings with $\Gamma_{10}$ and $\Gamma_{20}$ the decay rate from level $|1\rangle$ to $|0\rangle$ and the dephasing rate between level $|2\rangle$ and $|0\rangle$ respectively, $\Delta_i=\Omega_i-\omega_i$ ($i=1$, 2) the detuning of the field $\varepsilon_i(\varepsilon_i)'$, and $\Omega_1$ and $\Omega_2$ the transition frequencies of $|0\rangle-|1\rangle$ and $|1\rangle-|2\rangle$ respectively. Considering that the coherence $\sigma_{21}$ is much less than the coherence $\sigma_{10}$ and $\sigma_{20}$ in a steady state, and the factor before $\sigma_{21}$ in coupling equations is the Rabi