Evanescent light–atom interaction detected by optogalvanic effect

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Abstract

An evanescent light penetrating an atomic vapour near a dielectric surface could be a probe for many atom-boundary phenomena. We show the possibility of very sensitive detection of the resonant atom–light interaction near the surface by using the optogalvanic effect for an evanescent wave. We observe a narrowing of the profile of the detected atomic line, and we point out some properties of the optogalvanic effect in the evanescent wave.

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1. Introduction

When a discharge in a gas is illuminated by radiation resonant with an atomic transition, a change in conductivity of the atomic medium is observed. This phenomenon is known as the optogalvanic effect (OG). The effect is due to the variation of the number of charges and the change of free electron temperature [1,2]. We performed an optogalvanic spectroscopy experiment with evanescent light to observe resonance transitions from atoms located very close to the surface. When an electromagnetic wave, propagating in glass or quartz, reaches a boundary of atomic vapour of low refractive index, produces the evanescent wave in the vapour when the angle of incidence is larger than the critical angle. The wave in the vapour has the form:

\[ E_y = E_0 e^{-i \frac{k_y}{d} \exp\left[ -i (\omega t - k_x x \sin \alpha) \right] } \]

(1)

where \( \omega \) is the light frequency, \( k_y \) is the wave number in the dielectric material, \( \alpha \) is the incidence angle and \( d \) is the penetration depth in the vapour:

\[ d = \frac{\lambda_\lambda}{2\pi \frac{1}{\sin \alpha / \sin \alpha_c} - 1} \]  

(2)

In Eq. (2), the parameters \( \lambda_\lambda \) and \( \alpha_c \) denote the wavelength in the vapour and the critical angle, respectively. The evanescent wave propagates along the interface between the glass and the atomic vapour (the \( x \)-direction), and its amplitude decreases exponentially with the distance from the interface (in the \( z \)-direction). An optogalvanic signal in an evanescent wave in a DC discharge was first observed in Ref. [3]. Here, we present that a similar effect appears for a radio-frequency (RF) discharge. We use this technique for a more detailed study of the line profile and the line shape.

2. Experimental

The experimental set-up is shown in Fig. 1. An argon quartz cell with pressure of 0.9 Torr and at room temperature has been employed. The shape of the cell, the discharge position and the two ways of injection of the evanescent wave are shown in Fig. 2. We excite the argon \( 4d[3/2]_2 \rightarrow 4p[5/2]_2 \) transition at \( \lambda = 801.6 \) nm from the metastable level, using a diode laser with an external cavity of Littman-Metcalf design (EOSI type 2001). It can be fine tuned over 30 GHz range. The factory line width is \( \sim 1 \) MHz. The RF oscillator (20 MHz) is capacitively coupled to the argon plasma by means of two flat external electrodes. A laser-induced change in the plasma
impedance is monitored through the corresponding changes in the regime of the oscillator. If the losses are slightly increased, the oscillator amplitude is correspondingly decreased, and that produces an observable change in the current of the oscillator [4–6]. As OG signal we take the voltage drop on the resistor R inserted in the DC supply circuit of the oscillator (cf. Fig. 1). To improve the signal-to-noise ratio, lock-in detection of the OG signal is applied by amplitude laser beam modulation. We observe the OG signal both when the side (position 2 in Fig. 2(a)) of the discharge is illuminated (longitudinal probing) as well as when the region of the discharge is probed by the evanescent wave (position 1 in Fig. 2(a)). The incidence of the light on the prism produces the evanescent light and a lot of scattered light (partially eliminated by the arrangement shown in Fig. 2(b)). The latter can disturb the OG effect originating from the evanescent light. Integrating $|E_{ev}|^2$ over $z$ from zero to infinity, we conclude that the total electric field of the evanescent wave in the vapour is proportional to the penetration depth $d$ [3]. Assuming that

$$y = \text{const} \times \frac{a}{\sqrt{(n_1/n_2)^2 \sin^2(\alpha_c + \Delta \alpha) - 1}},$$

where $a$ is constant, corresponding to the amplitude of the signal, $d$ is the penetration depth, $\Delta \alpha$ is the difference between the angle of incidence and the critical angle, $\Delta \alpha = \alpha - \alpha_c$. The points are the results of the measured OG signal.

3. Results and discussion

The OG signal as a function of laser light frequency for the threshold discharge voltage has Gaussian shape. OG signals for evanescent (profile 1) and longitudinal (profile
Fig. 4. OG signal for evanescent probing (1 – in Fig. 2a) and longitudinal probing (2 – in Fig. 2b), for equal light intensity. The solid curves represent a Gaussian fit. The reference F-P fringes are shown below. The number of points is decreased by a factor 5 in comparison with the experiment to make the figures clearer.

2) probing recorded at the threshold discharge voltage are presented in Fig. 4. The spectral width of the evanescent profile obtained from the Gaussian function fit equals 801 MHz with standard deviation of about 1 MHz. The longitudinal profile width is about 1210 (± 3) MHz, while the estimated Doppler width is about 740 MHz. Fig. 4 reflects...

Fig. 5. The narrowest, Gaussian fitted profile (solid line) for evanescent wave probing.
Fig. 6. The set of OG profiles as a function of the intensity of the discharge voltage (indicated in each of the panels). The profile (d) is the narrowest, but still surprisingly well fitted by a Gaussian. For the fitted profiles (solid curves), the resulting FWHM (with standard deviation in parentheses) is indicated in each panel. For profiles (a) and (b) the number of points is decreased by a factor 5 in comparison with the experiment to make the figures clearer.
truthfully the relative magnitudes in the signal. Both signals were obtained for laser power of about 3 mW. The possible power broadening should be the same for both resonances, therefore it does not affect the relative spectral widths between these two signals. We have also recorded OG signals for a discharge voltage greater than the threshold one. We have observed that the OG profile width depends on the discharge voltage, but the width of the evanescent profiles is always smaller than that for longitudinal probing. The narrowest evanescent wave profile obtained for a certain discharge voltage (see Fig. 5), which still can be fitted by a Gaussian, has FWHM = 605 MHz with standard deviation equal to 10 MHz. If we suppose that the shape corresponds to the Doppler width, our narrowest profile is a sub-Doppler one. In this case narrowing of the line may be interpreted as a result of a decrease of the \( x \)-component of the velocity of the atomic dipole. It can be induced by the interaction with the dielectric surface. On the other hand, one may expect the observed narrowing as a result of the limiting conditions of the discharge itself near the surface. An additional experiment will be necessary to confirm one of these two hypotheses.

4. Change of line profiles in optogalvanic resonances

During observation of the evanescent wave with the help of the optogalvanic effect we have checked the variation of the shape and the width of the detected OG signals. The metastable \( 4s\,{}^3\!P_2 \) state in argon is strongly populated during the discharge. For the threshold discharge voltage, the main source of ions is the ionisation from metastable states. The optical resonance causes a decrease of metastable state population and the OG signal has a negative sign. It is known [7,8] that for a certain discharge voltage (which is dependent on the laser intensity) the OG signal changes its sign. Fig. 6 presents a sequence of 8 OG (“evanescent”) line shapes. The profile (a) is taken for the threshold discharge voltage. After the initial increase of the OG signal spectral width, it decreases when the discharge voltage comes to the value for which the OG signal changes sign. Near this value the OG spectral width narrows significantly. The Gaussian fitted spectral width of the narrowest profile (d) is 605 MHz (±10 MHz), while the Doppler width is 740 MHz. The profiles (e), (f), (g) present a superposition of the OG signals with opposite sign. OG signal conversion was observed in Refs. [7,8], but the sequence of OG resonances was taken as a function of the laser light intensity. Profiles (e), (f), (g) and (h) cannot be fitted by a Gaussian function.

A similar dependence appears for longitudinal probing. We can find the condition for the narrowest Gaussian profile, but we never obtain the sub-Doppler width. This confirms that narrowing is related with the evanescent way induced optogalvanic effect, but at the moment we do not know the physical origin of the narrowing. We plan a conclusive experiment in the near future.

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