Spectroscopic measurements of the evanescent wave polarization state

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Abstract

We applied optogalvanic spectroscopy to observe Zeeman effect in the evanescent wave in Ar gas with the help of a single-mode diode laser. The use of an homogenous external magnetic field enabled us to observe different $\pi$ and $\sigma$ Zeeman split lines contribution. We studied two orthogonal directions of external magnetic field and two orthogonal polarizations of the incident wave with respect to the plane of incidence. The analysis of relative line strengths leads to the determination of the polarization state of the evanescent wave.

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1. Introduction

Polarization properties of electromagnetic waves become particularly important, when we consider propagation in media with boundary conditions. Examples include optical fibers and planar waveguides or simply the interface between media with different refractive indices. Let us consider total internal reflection, a phenomenon which is underlying the important domain of guided waves and is thus crucial for optical information transmission and processing. In contrast to common plane waves propagating in extended media, the planes of constant phase and constant amplitude are not parallel for the evanescent wave. This property of the evanescent wave (called inhomogeneity) is connected to the non-transversality of electric or magnetic components of the electromagnetic field.

The polarization behavior and features of the evanescent wave are rarely considered in details in the optics literature [1,2]. If the incident beam is linearly polarized in the plane perpendicular to the plane of incidence (TE polarization), then the Fresnel equations predict evanescent wave to conserve that polarization. However, if the incident wave is polarized in the plane of incidence (TM polarization), then the evanescent wave is predicted to have the polarization of the elliptical character having its electric vector in the plane of incidence [1,2].

We propose to apply a Zeeman effect to investigate the polarization properties of the evanescent wave. We employ an evanescent wave spectroscopy (see e.g. [3]) for argon atoms using sensitive optogalvanic detection [4]. Split Zeeman $\pi$ and $\sigma$ components of the atomic transition appear in the absorption spectra for appropriate light polarization direction according to the external magnetic field [5].

2. Theory

Let us consider the total internal reflection of the light on the border of two dielectric media (see Fig. 1).

It is well known that when a plain electromagnetic wave reaches the interface from the dense medium and when the angle of incidence is over the critical one $\theta_c = \arcsin(n_2/n_1)$, the total internal reflection occurs. So called evanescent wave is present in the dilute medium. The angle of refraction becomes imaginary and the evanescent wave is described by the wave vector $\mathbf{k}$ with the complex $z$ component:
One can see that evanescent wave propagates along the boundary of two dielectrics and decays exponentially in the direction normal to the border plane.

From Fresnel equations one can calculate the components of the electric field vector of the evanescent wave in the dilute medium \[1,2\]:

\[
\frac{E_{\text{TM}}}{E_i} = \frac{2 \cos \theta \sqrt{\sin^2 \theta - n_{21}^2}}{\sqrt{1 - n_{21}^2}} e^{(-\delta_{\text{TM}}/2)},
\]

\[
\frac{E_{\text{TE}}}{E_i} = \frac{2 \cos \theta \sin \theta}{\sqrt{1 - n_{21}^2}} e^{(-\delta_{\text{TE}}/2)},
\]

where \( n_{21} = n_2/n_1 \).

Here TM indicates a linear polarization of the incident beam in the plane of incidence and TE indicates the polarization of the incident beam perpendicular to the plane of incidence. The quantities \( \delta_{\text{TM}} \) and \( \delta_{\text{TE}} \) denote the phase shift acquired by the TM and TE components of the electric vector after total internal reflection.

For the considered planar border between two media for any case of polarization of the incident wave it is sufficient to perform calculations and measurements for TE and TM polarizations only.
The relative time-averaged values of the real part of the electric field vector components (called then mean-square values) in the evanescent wave are shown in Fig. 2.

According to [2] and formulas (4)–(6) one can expect that if the incident beam is TE polarized the evanescent wave has linear polarization too with its electric vector being perpendicular to the plane of incidence. If the incident beam is TM polarized, the components $E_{tx}$ and $E_{tz}$ are phase shifted by $\pi/2$, so the evanescent wave has the polarization of elliptical character, having electric vector ellipse lying in the plane of incidence (see Fig. 3).

The idea of the measurements was to apply a magnetic field in different directions according to the electric vector of linearly polarized incident wave and with respect to the plane of incidence. This way different contributions of the Zeeman split lines to the evanescent wave spectroscopy signal were predicted [6]. Because the number of atoms in the volume created by the evanescent wave was small and absorption signals were extremely weak, we decided to use the optogalvanic technique for a more detailed study of the lines profiles [4,7]. The possible influence of the discharge electric field on the results was taken into account according to [8–11] and found to be negligible.

3. Experimental

The experimental setup which is shown in Fig. 4, consisted of a cylinder shaped glass cell with facility of change the argon pressure, constant magnets, radiofrequency (RF) generator and Fabry–Pérot interferometer. Argon atoms were excited using a single-mode diode laser with external cavity of Littman–Metcalf design (EOSI type 2001). Fabry–Pérot interferometer, with a free spectral range $724 \, \text{MHz}$, let us calculate the current relative frequency of the laser radiation when scanning.

The principle of the optogalvanic (OG) effect is to illuminate the electric discharge region in a gas by electromagnetic radiation resonant with an atomic transition and to observe changes in conductivity of the atomic medium [12,13]. The effect is caused by the variation of the number of charges and the change of free electron temperature in the gas. In the experiment the RF discharge with external electrodes was used [7]. The RF generator (20 MHz) was
coupled to the argon plasma by means of two flat external electrodes. A laser-induced change in the plasma impedance was monitored by measuring the current in the generator supplying circuit. To improve the signal-to-noise ratio, a lock-in detection was used. The amplitude of the laser beam was modulated by a chopper.

To create the evanescent wave a glass prism with refractive index of 1.51 was glued to the cell. Thanks to asymmetrical prism shape, back reflected light was strongly reduced. To prepare the linear polarization of incident beam as pure as possible the single-mode optical fiber and two polarizers (extinction ratio $10^{-5}$) with half-wave plate between them were used.

The magnitude of applied external magnetic field ($B$) was set by proper adjustment of the distance between two constant magnets. The value of $B$ was changed from 0.08 to 0.19 T and was sufficient to resolve all of the Zeeman components. Thanks to the size of the evanescent wave volume, magnetic field in this area was treated homogenous.

The following transitions were observed: $4s^2[1/2]_0 \rightarrow 4p^2[3/2]_1$ and $4s^2[3/2]_2 \rightarrow 4p^2[5/2]_2$ (Racah coupling, Fig. 7. The scheme of the main part of the experimental setup (not to scale): (a) TM polarization and (b) TE polarization of the incident beam.

Fig. 8. Optogalvanic signals of the evanescent wave (angle about 5° above critical) with applied external magnetic field (0.15 T) for configurations “1” and “2” with marked $\pi$ and $\sigma$ Zeeman split lines contribution. Indexes || and $\perp$ denote direction parallel and perpendicular to the plane of incidence, respectively.
Exemplary signals with applied external magnetic field for appropriate configurations are presented below (see Fig. 8).

Depending on the configuration of external magnetic field, observed \( \pi \) and \( \sigma \) lines correspond to different components of the electric field vector of the evanescent wave.

In configuration “1”, where magnetic field is perpendicular to the plane of incidence only \( E_{y} \) may be associated with the \( \pi \) component. Both, \( E_{z} \) and \( E_{x} \), may be associated with the \( \sigma \) component.

In the configuration “2”, where the magnetic field is parallel to the plane of incidence only \( E_{x} \) may be associated with the \( \pi \) component. Both, \( E_{y} \) and \( E_{z} \), may be associated with the \( \sigma \) component.

Among the four 8a–d cases the most interesting are 8b and c. In the 8b case, we have got the linearly polarized incident wave with its electric vector and the magnetic field directed perpendicular to the plane of incidence, so being parallel to each other. Fresnel equations predict in that case the evanescent wave to “conserve” the polarization of the incident wave, which means the evanescent wave is linearly polarized in the plane perpendicular to the plane of incidence. Therefore, we should observe \( \pi \) line only.
The σ lines should be absent. In Fig. 8b, π line dominates but some residual σ lines are present.

In the case 8c, we have got the magnetic field directed along the “propagation” direction of the evanescent wave and the electric vector of the incident wave lying in the plane of incidence. Fresnels equations predict for that case the elliptical character of the polarization of evanescent wave. We should observe both π and σ lines of comparable intensities. In Fig. 8c, π and σ lines of comparable intensities are present. The presence of weak, residual σ lines in 8b case and of π line in 8a or d case shows the limits of our experiment. Despite the fact, that the prism has special asymmetric shape, still some scattered light was present. It came from the laser beam striking the prism surfaces (roughness \( \lambda/4 \)). This radiation influenced the discharge in whole its volume and was impossible to suppress or distinguish from evanescent wave signal.

In order to make a conclusion about the evanescent wave polarization state, we consider the relative contributions of the π and σ components to the recorded spectra. Since the Gauss approximation of the line profiles is excellent (see Fig. 6), it is sufficient to take into account the ratio of the lines intensities only. However the line-shapes in the evanescent wave absorption spectroscopy [3,16] and in the optogalvanic spectroscopy near surfaces [17] are of a great importance for certain conditions. We define the ratio of π and σ lines intensities and show their dependence on the angle of incidence in Fig. 9. For cases 8a, b and d, we take into consideration residual lines and treat them as appropriate π or σ lines. These ratios for TE polarization case in the configuration 2 (Fig. 9b) and for TE and TM polarization cases in the configuration 1 (Fig. 9a) should be equal to zero, according to the theoretical calculations. They are not and it shows our experimental limits. These ratios for TM polarization case in the configuration 2 (Fig. 9b) present literally the elliptical character of EW. However the agreement between experimental data shown in Fig. 9b (\( A_\pi/A_\sigma \) ratio in configuration “2” for TM polarization) and calculations based on the Fresnel equations shown in Fig. 2b is not satisfactory.

For further analysis, we compare experimental amplitudes of σ components (configuration “2”) for TM and TE polarization of the incident beam with theoretical transmission intensity coefficients. The experimental amplitudes ratio \( A_{TM}/A_{TE} \) and the theoretical ratio \( \langle E_{2}^{\pi} \rangle/\langle E_{2}^{\sigma} \rangle \) are shown in Fig. 10. The scaling factor between the theoretical curve and experimental results is about 1/4. This is probably associated with the anisotropy of the gas medium in close vicinity (\( \lesssim 150 \text{nm} \)) of the prism surface. The proximity of the surface causes that optical properties of atoms depend on the direction of polarization of the evanescent wave. The magnitude of that modification depends on the direction of the induced atomic dipole according to the border plane.

5. Conclusions

We observed the Zeeman effect for the atoms interacting with the evanescent wave and determined the polarization state of the evanescent wave.

The experimental data proved literally the linear character of the polarization of the evanescent wave for the TE polarization of the incident beam. In the TM polarization case the data gave strong experimental confirmation of predicted elliptical character of the polarization of evanescent wave. Because of the non-negligible yield of scattered light this could not be accurately measured quantitatively. A considerable different experimental approach to the problem considered in this paper has been employed by the use of polarization sensitive and light-emitting organic nanoaggregates [18].

References