Spectrograph coupled with CCD module for high resolution spectroscopy measurements

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Abstract. A CCD-line module is built to upgrade conventional spectrograph to the CCD ability of advanced data acquisition as well as a cost-effective solution to the plasma diagnostic spectroscopy measurement needs. The CCD module is adapted to the ISP-51 (Lomo-Russia) spectrograph, used for light dispersion and as a wavelength pre-selector when a Fabry-Perot interferometer is positioned into the parallel optical path of the spectrograph. A high-resolution spectrometer system is developed both computerized and easy to maintain. The main advantage over conventional method of spectral line profile registration is achievement of single-shot capability. Thus the line profile distortions caused by intensity fluctuations, which occur during the scanning process are eliminated. The capability of the designed spectrometer are presented with the measurements of the resolved superfine structure of the Cd I 480 nm spectral line profile as well as analyzing Ar I 738.4 nm spectral line profile broadening resulting with the gas temperature determination of argon inductively coupled plasma at low pressure and applied power.

1. Introduction
Optical emission spectroscopy (OES) provides simple non-disruptive technique for gaining information about the main plasma parameters. Measurement of the spectral line profile is a powerful tool in plasma diagnostics of gas discharges. The gas temperature and electron density could be obtained from analysis of the broadening mechanisms which influence to the experimental profile. The proper description of the spectral line shape requires high spectral resolution of the detecting system. Sometimes it is necessary also to achieve a high temporal resolution of a light signal in a dynamical regime of the gas discharge in respect to the pressure or power increase. Last but not least requirement for low-cost and less-time consuming process should also be taken into account.

The most common methods for high-resolution line profile measurements use scanning Fabry-Perot spectrometers [1]. This registration is accomplished by variation of the refractive index of the medium between the interferometer plates (pressure scanning) or by piezoelectronic variation of the plate separation. These high resolution spectrometers are rather expensive and the spectral line profile originates from a large number of events time-averaged in order to scan the whole spectral line profile.

In the literature are reported [2–4] different solutions to acquire high-resolution spectroscopy measurements by means of combination of Fabry-Perot interferometer (FPI) with monochromator or optical multichannel analyzer.

This study, being an extension of the method for analysis of the spectral line profiles developed in [5–7], presents a solution to acquire high-resolution spectrometer system by upgrading conventional spectrograph to the CCD ability. A CCD-line module, stand-alone type, is coupled with the...
spectrograph. The module is aligned parallel or cross-vise to the spectrograph dispersion in case when the FPI is mounted inside of the spectrograph. The module is adaptable to the conventional spectrographs and designed to works under Windows.

The aim of the present study is achievement of instrumentally low-cost effective solution ensuring high enough resolution of the spectrometer system in wavelength and time necessary in spectroscopy measurements of the spectral line profile structure or broadening.

The paper is organized as follows. The CCD-line module built for spectral line profile recording and coupled with spectrograph and FPI incorporated in it as well as the experimental set-up, providing inductively driven argon discharge at low pressure are presented in section 2. The broadening mechanisms having influence on the width of spectral line profile are given in section 3. The experimental results, presented in section 4, are orientated into two aspects. The resolution of the designed spectrometer system is illustrated with a record of a Cd I 480 nm superfine line structure. Results for the gas temperature of argon inductively coupled plasma at low pressure and applied power, obtained through measurements of Ar I 738.4 nm spectral line profile broadenings, are also presented.

2. Experimental details

2.1. Experimental set-up

A schematic illustration of the experiment built for gas temperature determination is presented in figure 1. The plasma source is inductively driven discharge at low pressure in argon gas, the same as described before [8, 9], consisting of a driver and a volume for plasma expansion. The driver region is in the classical form of the cylindrically shaped inductive discharge with a 9-turns coil positioned over the quartz discharge tube. The high frequency ($f = 27$ MHz) applied power is varied in the limits $P = (75 – 195)$ W. The argon gas pressure is $p = 16$ and $26$ mTorr. The light coming from the first chamber is collected by an optical waveguide (through a hole in the copper shield) positioned at distance of $0.5$ cm from the end of the discharge tube and $3.5$ cm from the end of the coil.

![Experimental set-up](image)

**Figure 1.** Experimental set-up.

![Registered interferogram of the Cd I spectral line $\lambda = 643.8$ nm.](image)

**Figure 2.** Registered interferogram of the Cd I spectral line $\lambda = 643.8$ nm.

The spectrograph ISP-51 (Lomo-Russia) is built on Fösterling’s three prism arrangements. The diameters and the focal lengths of the objectives are $d_1 = d_2 = 50$ mm, $f_1 = 304$ mm and $f_2 = 270$ mm respectively. A FPI (IT-51 from Lomo-Russia) is positioned into the parallel optical path of the dispersion system. The diameters of the FPI plates are $50$ mm, their reflection coefficient is $R = 90\%$ in the visible region and their flatness is $\lambda/50$. The cavity spacing of the FPI is provided with intermediate rings $t = (0.3 – 30)$ mm and for $\lambda = 600$ nm the free spectral range is $(16.67 – 0.17) \text{ cm}^{-1}$. Thus the theoretical resolution for $t = 10$ mm ring thickness at $\lambda = 546$ nm is $\lambda/\delta\lambda = 1.04\times10^6$. A
waveguide is used for collecting and transmitting the light from the plasma to the spectrograph entrance slit. With a rectangular cross-section of the end it is ensured both a good coupling with the spectrograph entrance slit and a good illumination of the central orders of the ring pattern displayed on the monitor. The interferogram of Cd I spectral line $\lambda = 643.8$ nm is taken with FPI plate separation of 14 mm and shown in figure 2.

A CCD-line module lies at the photo-cassette place. The CCD-line is aligned cross-wise to the dispersion direction of the spectrograph at the center of the photo-cassette, where a selected wavelength is positioned. A PC is used for observation of the interferograms in real time and for data acquisition.

2.2. CCD-line module

CCD-line module is a stand-alone type, light sensitive, scanning device, working in the spectral range from 400 nm to 1000 nm with a high sensitivity up to 500 V/(lx·sec) at 660 nm. It has active sensor length of 28.7 mm (B4 size). These characteristics are reached due to the use of the special B/W sensor ILX 551B from SONY, which incorporates 2048 usable pixels with size: 14 x 14 µm. The entire communication with the external unit (PC), including programming, amplifier gain, time of exposure, statistics, data transfer etc. is realized by the universal, internal Enhanced Parallel Port (Type EPP 1.9). The catalog spectral sensitivity of the sensor is shown in figure 3.

In order to achieve a smaller current consumption, CMOS circuits as the microcontroller Atmega 8M and the Analog-to-Digital Converter MCP 3208 are used. The maximum power consumption of 60 mA at 12 V allows battery supply for low noise measurements.

![Figure 3. Spectral sensitivity of the CCD-line.](image)

![Figure 4. Functional block-diagram of the CCD-line module.](image)

The functional block-diagram of the CCD-line module is shown in figure 4. The sequence of the connection of the individual blocks corresponds to the sequence of data processing and transfer. The analog signal coming from sensor is amplified and sampled by 4 levels S/H amplifier OP490/SMP04 and later converted by the 12-bit ADC. These digital data are accumulated and primary processed in the microcontroller, which supports the EP Port and periodically transfers the sampled data to the external units i.e. PC.

The specially designed PC program works under Windows and allows real time measurements control and visualization of the results.

3. Spectral line profile broadenings

For plasma diagnostic purpose, high spectral resolution is an essential requisite for measuring small widths of spectral line. The spectral line profile is formed by different mechanisms of interactions which cause its broadening. The experimental profile is a convolution of various Lorentzian ($L$) and...
Gaussian \((G)\) distributions, resulting from the plasma source and those from the instrument used, with half-widths \(\Delta v_L\) and \(\Delta v_G\), respectively, which results in a Voigt function \(\Psi(v-v_0)\):

\[
\Psi(v-v_0) = \int_{-\infty}^{\infty} L(y)G(v-v_0-y)dy = \frac{2\sqrt{\ln 2}}{\pi \sqrt{\pi}} \frac{\Delta v_L}{\Delta v_G} B \int_{-\infty}^{\infty} \frac{e^{-y^2}}{\Delta v_G} \ln 2 + \left[ \frac{2\sqrt{\ln 2}}{\Delta v_G} (v-v_0) - y \right]^2 dy,
\]

where \(v_0\) is the wavenumber \((v_0 = \frac{1}{\lambda}, \lambda\) is the wavelength) of the spectral line and \(B\) is the line intensity integrated over the profile. Under the gas discharge conditions the shape of the spectral line profile emitted from the plasma is formed by several broadening mechanisms: natural due to the finite life time of the excited states with half-width – \(\Delta v_{LN}\); Doppler, thermal motion of the emitters – \(\Delta v_{GD}\); Van der Waals, interaction between the emitting atoms and the other species – \(\Delta v_{LW}\); Stark, interaction of the emitters with the electrical fields of the nearby charged particles – \(\Delta v_{LS}\). The instrumental effects also should be taken into account in the analysis of the spectral line profile. The instrumental function of FPI used is Voigt function resulting from Gaussian function due to the plate defect or their flatness \(\Delta f\), \(\Delta v_{Gi} = \frac{\Delta f}{t} v_0\) \((t\) is the plate separation\) and Lorentzian function, due to the reflection coefficient \(R\) of the plates, \(\Delta v_{Li} = \frac{1-R}{2\pi \sqrt{R}}\).

The resulting half-width of the Voigt profile is: \(\Delta v_v = f(\Delta v_G, \Delta v_L)\), where \(\Delta v_G = \sqrt{\sum_{j=1}^{2} \Delta v_{Gj}^2 + \Delta v_{Gi}^2}\) and \(\Delta v_L = \sum_{k=1}^{4} \Delta v_{Lk} = \Delta v_{LN} + \Delta v_{LW} + \Delta v_{LS} + \Delta v_{Li}\). The approximation of experimental points with Voigt function according to the Maquardt-Levenberg procedure give the values of \(\Delta v_L\) and \(\Delta v_G\). For obtaining the half-widths related with the plasma parameters – \(\Delta v_{GD}\), \(\Delta v_{LS}\) and \(\Delta v_{LW}\) – it is necessary to exclude the instrumental half-widths and the natural broadening which is negligible in many cases compare to the other mechanisms. The gas temperature \(T_g\) is related with the Doppler broadening width \(\Delta v_{GD} = 7.16 \times 10^{-7} v_0 \sqrt{\frac{T_g}{\mu}}\) \((\mu\) is the atomic mass of the gas) whereas the electron density is related with the Stark broadening width.

4. Experimental results

The spectrometer system (spectrograph, with FPI incorporated in it, coupled with CCD-line module) is tested (in respect to its resolution) recording a spectral lines of Cd lamp (OSRAM). Part of the interferogram of the Cd I spectral line with \(\lambda = 480\) nm, registered with FPI plate separation \(t = 6\) mm is presented in figure 5. This line has superfine structure and consists of five components. The separation of the components \(\delta v\) toward the central transition \(5^3P_1 - 6^3S_1\) as well as their relative intensities are given in table 1, according to [10].

OES method for gas temperature determination of Ar inductively driven discharge, at low gas pressures \(p = 16\) and \(26\) mTorr and low applied power in the limits \(P = (75 - 195)\) W, from the Doppler broadening of the spectral line profile of Ar I \(\lambda = 738.4\) nm is applied. The registered interferogram, at FPI plate separation \(t = 14\) mm, is calibrated from pixel to wavelength scale \((\text{cm}^{-1})\). After normalizing each maximum (± 8 orders) of the interferogram to an unit area, all the maximums are superimposed on a resulting profile including more than 400 points. At very low light intensity conditions it is necessary to average over a hundred events in order to achieve a reasonable signal to
The experimental data are fitted with Voigt profile, consisting of nearly constant Lorentzian part caused by the instrumental broadening $\Delta V_L = \Delta V_{Li}$ and Gaussian part caused by the instrumental $\Delta V_{Gi} = 0.014 \text{ cm}^{-1}$ and Doppler broadenings. Under the conditions of the experiment, Van der Waals and Stark broadenings are small compared to the Doppler broadening. The experimental points and the fitting Voigt function for $\lambda = 738.4 \text{ nm}$ spectral line are shown in figure 6.

Table 1. Superfine structure of the Cd I spectral line $\lambda = 480 \text{ nm}$.

| $\delta \nu$, cm$^{-1}$ | -0.266 | -0.060 | 0     | +0.127 | +0.337 |
|------------------------|--------|--------|-------|--------|--------|
| relative intensity    | 4      | 3      | 10    | 1      | 2      |

Figure 5. Interferogram of the superfine structure of the Cd I spectral line with $\lambda = 480 \text{ nm}$.

Figure 7 presents the results for the gas temperature obtained for the first chamber of the source, within an error of 5% from the fitting procedure.

The determination of the gas temperature values closed to the room temperature at low pressure ($p = 16 \text{ mTorr}$) and low applied power as well as the registration of the weak tendency of the gas temperature with the applied power increase, are fairly reasonable. The results obtained at $p = 26 \text{ mTorr}$ are in good agreement with those presented in [11].

Figure 6. Spectral line profile of the Ar I $\lambda = 738.4 \text{ nm}$ obtained for gas discharge condition in the first chamber $p = 26 \text{ mTorr}$ and $P = 130 \text{ W}$.

Figure 7. Gas temperature dependence on the applied power obtained for the first chamber.
5. Conclusions
A CCD-line module adaptable to the spectrograph ISP-51 is coupled to provide spectroscopy measurements for plasma diagnostics. The combination of CCD module and spectrograph with FPI incorporated in it performs a spectrometer system with a single-shot capability. The resulting set-up enables to resolve the superfine structure of spectral lines.

The spectrometer system, used to measure the Ar I 738.4 nm spectral line profile with high resolution in wavelength, is also applied to investigate the gas temperature and its dependencies on pressure and applied power in inductively driven discharge. High accuracy in a less time consuming process as well as low cost effective solution is achieved.

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