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Competition effect between rotational levels in plasma diagnostics*

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A method for plasma electron density measurements is described. The method uses the competition effect between rotational levels of the rotation-vibration band of CO_2 at 10.6 μm. The investigated plasma, placed in the resonator cavity, changes the laser frequency and the resulting power changes of the competing lines are detected by a differential piezoelectric detector. The operating frequency is stabilized to the equal-intensity point by the use of antenna effect stabilization. Measurement of the electron density in the helium plasma is made.

1. Introduction

The determination of plasma properties possesses continuous difficulties, when results of quantitative experiments are to be compared with theory. Electron, ion and atom densities, electron temperature and ion temperature are the parameters for which quantitative data are desired. Laser methods can give information about most of these quantities over a wide range of plasma parameters and have the advantage that the plasma is usually not perturbed [1]. We report a method for determining the electron density in low-temperature plasmas.

The refractive index n of a plasma for electromagnetic radiation of angular frequency ω is given

$$n = [1-(\omega_p/\omega)^2]^{1/2} \approx 1-1/2(\omega_p/\omega)^2, \; \omega \gg \omega_p \tag{1}$$

where: $\omega_p = (4\pi n_e e^2/m_e)^{1/2} = 5.6\times 10^4 n_e^{1/2}$, [rad s^{-1}],
n_e – electron density,
m_e, e – electron mass and charge, respectively.

Thus, the electron density n_e of plasma can be determined by measuring its refractive index for radiation of a suitable frequency. There exist a number of techniques for determining the change of the optical length due to plasma. The most known are those which use interferometers, e.g., the Mach-Zehnder, Michelson, Jamin or three-mirror intra-cavity laser interferometers [2]. Measurements usually involve the shift of the interference fringes due to the investigated

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plasma. The sensitivity of the method depends on both the wavelength of the laser radiation and the minimum measurable shift of interference fringes.

The technique described in this paper detects the change in the resonant frequency of the optical cavity due to the introduction of plasma within the cavity. The resulting frequency shift can be detected by two methods. The first one was used by Gerardo et al. [3], and is a modification of the well-known three-mirror interferometer method. A three-mirror cavity was employed, the plasma being placed in the laser section. According to this method the changes of the laser frequency, due to the shift in the optical length of the cavity resulting from the introduction of the plasma bring about the changes of the transmission of the reference cavity and the output light intensity. In this way the authors [3] measured electron densities of 2×10^{13} electrons/cm^3 using 47.5 cm-discharge tubes with an excellent resolution. The other method detects the resonant frequency shift by heterodyne methods thus it is capable of measuring electron densities down to about 10^{10} electrons/cm^3 [4].

We report a method in which strong competition effects between rotational levels of the rotation-vibration band of standing-wave CO_2 laser have been used for the measurement of the laser frequency shift caused by plasma. While the laser oscillates with a single frequency at a given rotational sublevel other rotational levels will couple (due to collisions) their stored energy into the lasing transition. As the cavity mode is tuned away from the Doppler centre of the lasing transition, the oscillation conditions became more favourable for another transition. During a narrow frequency interval there exists a competition region in which both rotational levels compete for the total inversion of the same and higher vibrational levels and their rotational sublevels. In general, the competing transitions have different upper (00°1) and lower (10°0) rotational levels, but in our experiments we have observed the competing P- and R-transitions with equal J number, and shearing the same terminal laser level. The inter-rotational-level competition region can be hardly observed, since the total out-

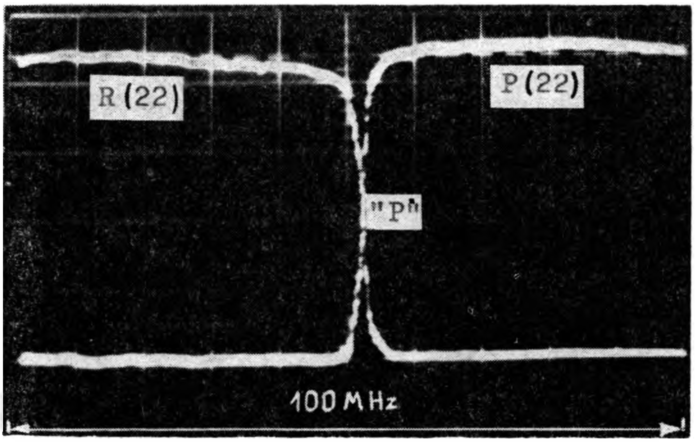

Fig. 1. Intensity changes of two competing lines as a function of laser frequency. "P" – equal-intensity point

put power of the laser remains approximately constant and the transition switching occurs over a frequency interval of a few megahertz. So narrow an interval is due to intensity-dependent anomalous dispersion arising from saturation. The intensity of the lines in the competition region is strictly proportional to the frequency (Fig. 1), thus, the frequency changes can be measured in terms of line intesnity fluctuations.

2. Experimental arrangement

The water cooled CO_2 laser with a plasma cell inside the cavity and an optical set-up, shown schematically in Fig. 2, were placed on a heavy granite slab located in a cellar laboratory. The pyrex discharge tube 60 cm long and 1.4 cm in diameter, filled with gas mixture $CO_2:N_2:He = 1:1:4$ under total pressure of

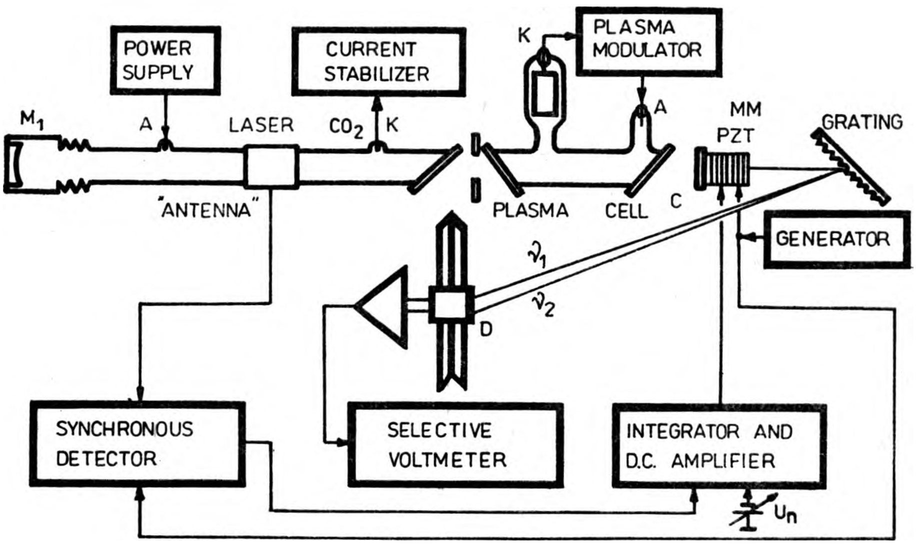

Fig. 2. Detailed schematic diagram of the plasma diagnostic setup

12 Torr was terminated by NaCl Brewster-angle window at one end and by an adjustable mirror mount (MM) with mirror (M_1) at the other one. The total reflector (M_1) of 5 metre-radius was a gold-coated BK–7 glass mirror. The laser radiation was coupled out of the cavity by a 90%-reflecting Ge output coupler (C) mounted on piezoelectric transducer. The length of cavity, with a 10 cm long plasma cell (ended with NaCl Brewster-angle windows), was 118 cm. The discharge tube was excited by means of unstabilized high-voltage d.c. power supply with 10 V (peak to peak) ripple voltage. The current of the discharge tube was stabilized by a current stabilizer connected to the laser tube from the cathode side. The discharge was maintained between a hollow-cylindrical nickel cathode of diameter of 2 cm and 1.5 mm-diameter tungsten anode. The total gas volume was 1 dcm^3 (including the reservoir). The laser output power for sealed operation

(with the plasma cell inside the cavity) was 2 watts. A bar of metallic foil, 12 cm in width, wound around the water jacket ("antenna") was used to stabilize the operation point [5]. In order to reduce the electro-magnetic interference the antenna was coated with an insulating foil and grounded. A plane diffraction grating (153 lines per mm) was used to separate two competing lines (ν_1, ν_2). The changes of laser lines intensities due to plasma were detected by piezo-electric differential detector (D). Figure 3 shows the signal obtained from the synchronous detector with 100 MHz-tune of the laser frequency. The frequency (2100 Hz) of auxiliary modulation was chosen to avoid power supply ripple, harmonic components, oscillation in the laser discharge and to reduce the influ-

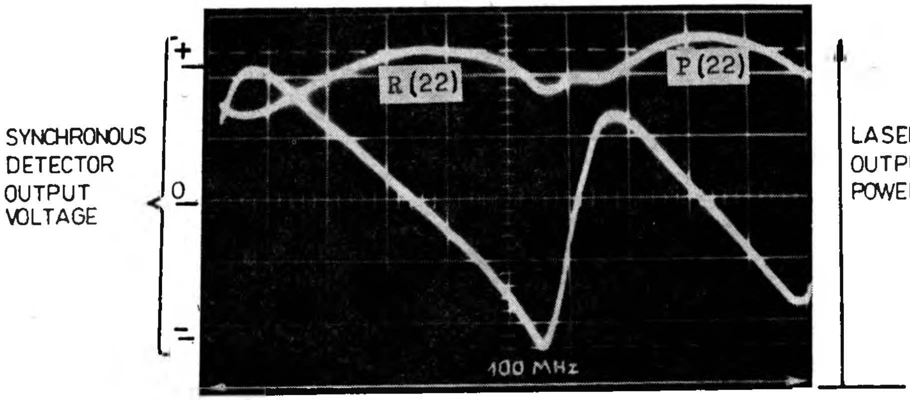

Fig. 3. Laser output power and simultaneous voltage from the synchronous detector as a function of laser freqeuency. The peak laser power is 2 W

ence of the laser internal noise (type $1/f$) due to vibration. Subsidiary misalignment of the laser of about 190 kHz was sufficient to obtain good operation of the frequency-control system. The operation point of the laser was stabilized in the competition region. The equal-intensity point ("P", Fig. 1) was chosen for laser operation since all expected effects, such as the intensity-dependent

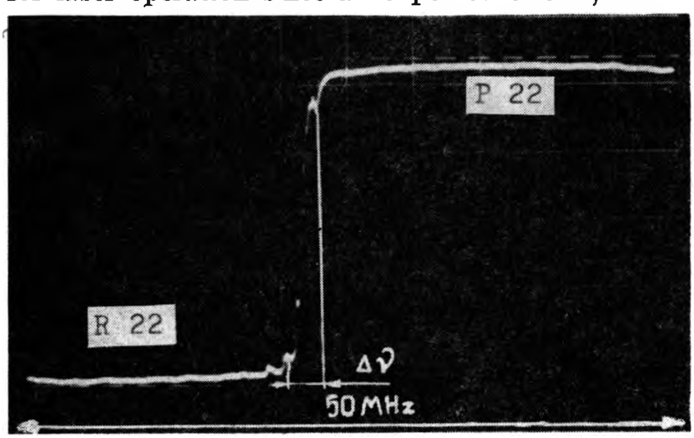

Fig. 4. Output voltage from differential detector as a function of laser frequency. $\Delta\nu$ – competition interval

gain and index of refraction, are equal for both transitions, and, moreover, the largest range of plasma density measurement is provided. Figure 4 shows output voltage from the differential detector when the laser frequency was tuned in the range of 50 MHz. As can be seen, the competition occurs over 3.5 MHz-frequency interval. Figure 5 shows the scaling curve obtained when the

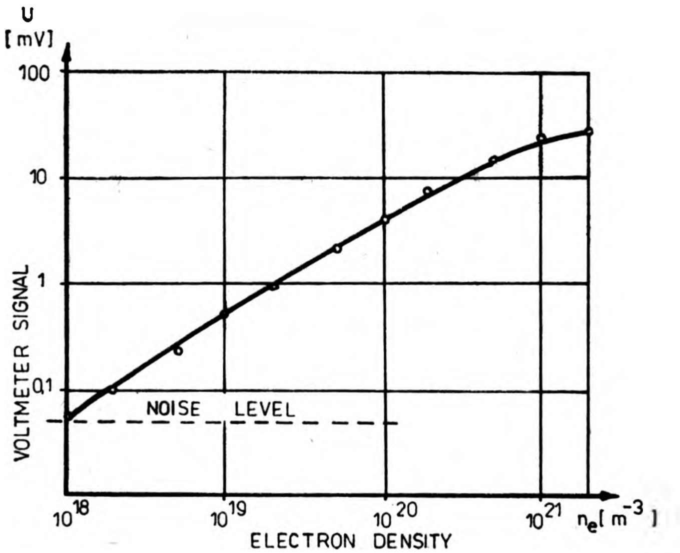

Fig. 5. Scaling curve of the plasma diagnostic setup

changes of the cavity length were due to piezoelectric transducer PZT (the operation of the laser was stabilized to the equal-intensity point). The frequency of scaling scan (17 Hz) was chosen to avoid the interference due to vibration (type $1/f$) and to provide a sufficient sensitivity of the differential piezoelectric detector (its sensitivity decreases by 1.3 dB/octave). The time constant of the frequency-control loop was 3 s, thus the cavity-length changes due to scaling scan were not stabilized. As can be seen, the intensity changes of the competing lines in the competition interval are exactly proportional to the laser frequency changes. When the scan of the laser frequency due to the plasma (piezoelectric transducer in scaling measurements) is $\delta\nu$, the electron density in the plasma cell (10 cm long) can be calculated from a simple formula

$$n_e = 8.3 \times 10^{14} \times \delta\nu \ [\mathrm{m}^{-3}]. \tag{2}$$

The electron density in the plasma cell was measured in the setup presented, using the plasma cell filled with helium under the total pressure of 665 Pa (5 Torr). The plasma was excited by an h.v. modulator. The frequency of modulation was 17 Hz and the peak hight of current discharge was about 120 mA. The electron density in the investigated plasma was found to be $2.7 \pm 0.3 \times 10^{18}$ m^{-3}.

3. Conclusions

The technique presented above is useful for measurements of plasma density in a wide range of 10^{18}–10^{21} m^{-3}. The sensitivity achieved in the presented setup is better than those obtained by using interferometers, and it is about one order lower than that obtained by heterodyne methods. The sensitivity of the presented method could be increased by using a laser having a better passive stability.

References

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Явление конкуренции ротационных уровнев в диагностике плазмы

Описан метод измерения концентрации электронов в плазме. Он основан на явлении конкуренции между ротационными уровнями вращательно-колебательной полосы в CO_2 для 10,6 μм. Испытаемая плазма, помещенная в полость резонатора, изменяет лазерную частоту, а вытекающие отсюда изменения мощности конкурирующих друг с другом линий обнаруживаются дифференциальным пьезоэлектрическим детектором. Система стабилизации частоты работы стабилизирует пункт работы с одинаковым напряжением при помощи стабилизации антенного эффекта. Измерена концентрация электронов в He плазме.