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Neon-Hydrogen Penning Plasma Laser in a Helical Hallow-cathode Discharge

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Abstract. A Penning plasma laser (PPL) operating at the NeI 585.3 nm and NeI 1.15 μm lines in Ne–H_2 mixture has been realized. Helical configuration of the electrodes was used. The dependence of the laser-pulse shape and output power on current pulse duration and amplitude values were investigated. Peak output powers of 1.5 W for the yellow line and 1.2 W for the IR line have been measured.

The population inversion mechanism for the 585.3 nm line is discussed in the frames of a model for PPL. The main factor maintaining the population inversion on both lines is depopulation of the Ne($1s_2$) level by Penning reactions with H_2.

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The Penning plasma laser (PPL), whose main principles of operation have been reported in [1, 2] is based on recombination population of the upper laser level (ULL) and depopulation of the lower laser level (LLL) by Penning reactions with buffer gas atoms or molecules. The growing interest in PPL in recent years is connected with obtaining strong pulsed lasing in the visible spectrum on the Ne atom transitions. Using e-beam pumping, at pressures of about 1 to 3 atmospheres, output powers of 60 kW/l are reached [3–6]. Moreover, it has been shown [7–10] that the obtained laser action might be not only pulsed but quasi-CW as well. Lasing at the NeI 585.3 nm line has also been reached in discharge lasers, using hollow-cathode discharge [11], hollow-cathode and mesh anode [12] or fast transverse discharge [7, 13, 14]. In spite of the lower output power ($\simeq 2.5$ W) they are very attractive due to their simpleness and the possibility to work in a pulsed repetitive mode.

Hollow-cathode discharge plasma is characterized by a beam component of non-Maxwellian electrons with energies much higher than the ionization potential of the atoms. Hence it is quite easy to get strong ionization and realize recombination population of the ULL in the hollow-cathode discharge plasma.

Using hydrogen as a buffer gas, by which the Penning channel of deexcitation of the LLL is accomplished, the process of recombination is also stimulated by more effective cooling of the electrons in the hydrogen medium.

The aim of this paper is to investigate Ne–H_2 PPL for which the active medium is the negative glow of a hollow-cathode discharge with helical configuration of the electrodes.

1. Experimental Setup

The laser-tube design used in these investigations is very similar to our He–Kr laser device which has been previously described in more detail [15]. Helical shape of the electrodes is chosen as a promising one for discharge stability at high currents and providing a high-voltage mode of operation.

The power supply provides current pulses up to 250 A at voltages up to 5 kV. A controlled spark gap is used as a switch element. The repetition rate of the pulses is 5 Hz. Changing the inductance and capacitance of the discharge circuit the duration of the current pulses may vary from 1 to 40 μs (measured at the base-line).

Shapes of the current and voltage pulses for different pulse durations are given in Fig. 1. The voltage pulse rises faster than the current pulse. The slope of the pulse-fronts changes for different durations, because of changes of inductance and capacitance in the discharge circuit. In fact, due to the inductance of the circuit it is not possible to obtain voltages over 1000 V on the laser tube and currents over 180 A when examining long laser pulses.

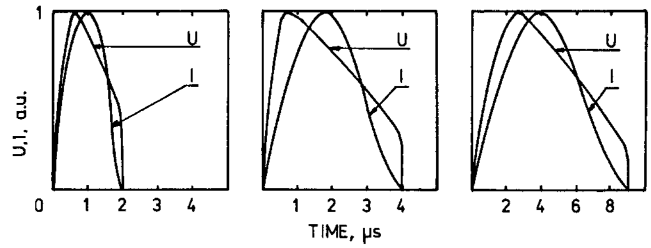

Fig. 1. Shape of the voltage pulse U and current pulse I for different pulse durations

Thus the same current can be reached at different voltages from the power supply, depending on the pulse duration: the longer the pulse, higher is the voltage.

The total pressure of the Ne–H_2 mixture is varied from 1 to 30 Torr. The Ne and H_2 pressures are varied from 1 to 10 Torr and from 0 to 20 Torr, respectively.

Hydrogen is let into the laser tube through a Ni tube, heated to a suitable temperature.

The laser cavity consists of dielectric coated mirrors with 99% and 99.9% reflectivity for the IR spectral region and 99.9% and 50%, 70%, 92% or 99% reflectivity for the yellow region.

The output power is measured by a calibrated PIN photo-diode.

The wavelengths of the laser lines are measured using an SPM-2 monochromator

Lasing on the NeI 585.3 nm and NeI 1.15 μm lines has been obtained.

2. Investigation of Lasing at the NeI 585.3 nm Line

The output power of the NeI 585.3 nm laser line is investigated at different discharge conditions: at different pressures of Ne and H_2, and different current pulse peak values and durations.

The change of the laser pulse shape at different current pulse durations is plotted in Fig. 2. The amplitude values are normalized to unity. As the current-pulse duration increases, the laser pulse moves from the afterglow towards the current pulse. At pulse durations over 9 μs the laser pulse is within the current pulse duration. The time delay of the laser pulse increases with the pulse duration increasing at a given peak current value but decreases with the increase of the peak current value.

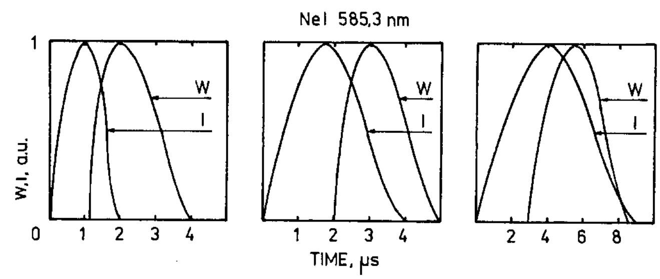

Fig. 2. Shapes of the current pulse I and NeI 585.3 nm laser pulse W at 2, 4, and 9 μs current pulse duration

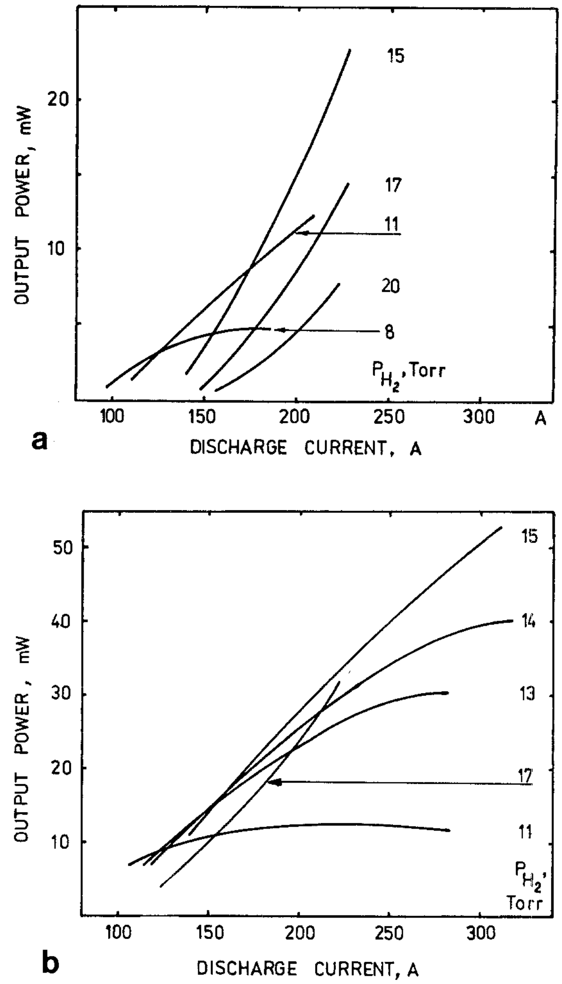

Fig. 3a, b. Dependence of the peak output power of the NeI 585.3 nm line on peak discharge current at 3 Torr Ne pressure and at various H_2 pressures and current pulse durations: **a** 2 μs, **b** 4 μs

The optimal pressures for lasing are 3 Torr Ne and 15 Torr H_2.

The dependence of peak output power on peak discharge current for optimal Ne pressure and different H_2 pressures is shown in Fig. 3a, b for two different current pulse durations – 2 and 4 μs. At low H_2 pressures the lasing saturates, but at optimal and over optimal H_2 pressures there is no saturation.

So, if a power supply providing higher voltages is used, the possibility exists for obtaining stronger laser action at higher hydrogen pressures.

The dependence of peak output power on peak discharge current at different current pulse durations and optimal Ne and H_2 pressures is shown in Fig. 4.

As it can be seen from Figs. 3 and 4, the highest laser efficiency is reached at pulse durations of 4 μs.

A peak output power of 1.5 W was measured at optimal Ne and H_2 pressures, 200 A peak current value and 4 μs duration of the current pulse. The output mirror used has 92% reflectivity. When using output mirrors of 70% and 50% reflectivity output powers of 0.5 W and 3 mW were measured, respectively.

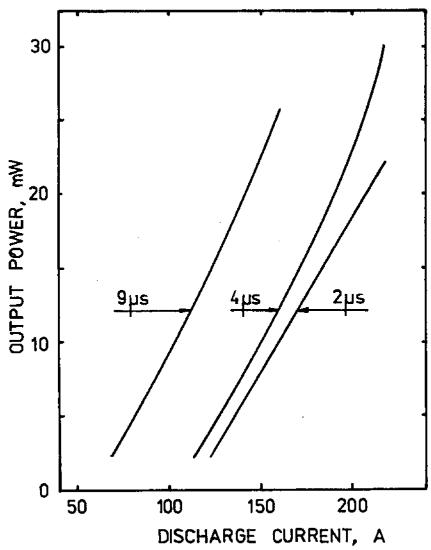

Fig. 4. Dependence of peak output power of the NeI 585.3 nm line on peak discharge current at different current pulse durations and optimal Ne and H_2 pressures

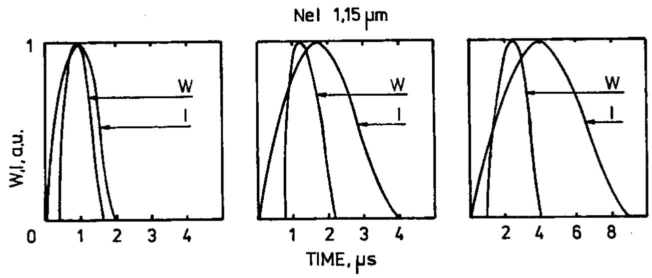

Fig. 5. Shape of the current pulse *I* and NeI 1.15 μm laser pulse *W* at 2, 4, and 9 μs current pulse durations

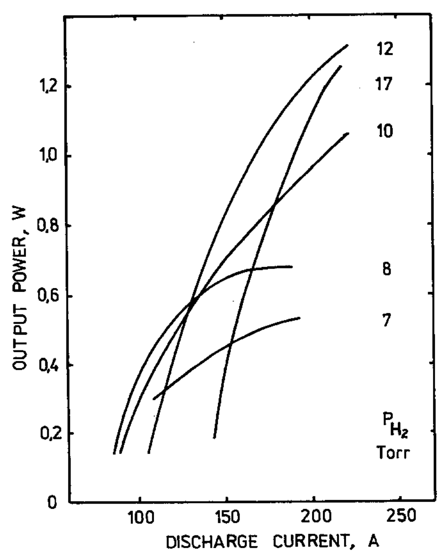

Fig. 6. Dependence of peak output power at the NeI 1.15 μm line on the discharge current at 3 Torr Ne, various hydrogen pressures and 2 μs current pulse duration

3. Investigations of Lasing at the NeI 1.15 μm Line

Shapes of the current pulse and the NeI 1.15 μm laser pulse are shown in Fig. 5. The laser pulse duration of this line is shorter compared to that of the 585.3 nm line and is within the current pulse duration for all pulse lengths investigated. Moreover, lasing at the 1.15 μm line occurs in the rise time of the current pulse, contrary to the case of the 585.3 nm line. The mode of operation which gives the most effective lasing is at a current pulse duration of 2 μs.

Optimal pressures of Ne and H_2 were investigated and were found to be 3 Torr and 12 Torr, respectively.

The dependence of output power on discharge current at optimal Ne and H_2 pressures is depicted in Fig. 6. Similarly to the situation of yellow lasing, there is no saturation of the output power with the discharge current increasing at optimal and higher than the optimal pressures.

An output power of 1.2 W was measured using an output mirror with 99% reflectivity, at optimal Ne and H_2 pressures and 200 A peak current value. No attempts have been made for optimization of the laser cavity.

4 Discussion

The laser action at the NeI 585.3 nm line obtained in these investigations is consistent with the model of PPL. In accordance with this model the population of the ULL can be considered as a result of recombination processes since laser action occurs in the afterglow or during the current pulse, but after the peak of the current pulse where recombination processes dominate over the ionization processes. Because of the high electron density and high pressures the electron temperature is not so high, thus providing an increased rate of recombination processes.

The fact that the laser operates at Ne pressures under 1 Torr does not confirm the assumption about the dominant role of the dissociative recombination as a main process for the ULL population. If we consider the rate constant for atomic to molecular ion conversion $k_c = 1.3 \times 10^{-31}$ cm^6/s [16] and the density of neutral Ne atoms of 10^{17} cm^{-3}, the characteristic time for molecular Ne ion formation is about 800 μs, which is much longer than the characteristic duration of the obtained laser pulses. Thus, for the explanation of the ULL population other kinds of plasmachemical reactions ought to be considered. For example: ion-ion recombination with negative hydrogen ions, as proposed in [16], or two-electron recombination.

The lasing at the 1.15 μm line is qualitatively different from the lasing at the 585.3 nm line. For all pulse durations laser action occurs during the current pulse and moreover in its rise time, so for the population of the ULL of 1.15 μm transition, the electron impact processes are evidently dominant.

In both cases (585.3 nm and 1.15 μm) there is no lasing under a certain threshold hydrogen pressure. This can be explained by a dominant role of the Penning reaction [between the $Ne(1s_2)$ level and hydrogen molecules] in the population inversion mechanism.

For lasing at the 585.3 nm line the threshold H_2 pressure is about 7 Torr. If we assume that the LLL is populated by radiative transitions and electron collisional processes from the ULL and is depopulated by Penning reactions with H_2, and if we assume the following values: electron density $n_e = 3 \times 10^{14}$ cm^3, electron temperature $T_e \simeq 0.5$ eV, Penning reaction rate constant for LLL ($1s_2$) $k_p = 1.2 \times 10^{-9}$ cm^3/s [6], transition probability from the ULL $A\widehat{2p_1} = 7.2 \times 10^7$ s^{-1}, electron collisional deactivation rate constant for the ULL, $k_d = 4 \times 10^{-7} \times T_e^{-1/2} = 5.7 \times 10^{-7}$ cm^3/s [6], we obtain for the necessary Penning admixture density N_{H_2} for laser action:

$$N_{H_2} \geqq \frac{A_{2p_1} + k_d n_e}{k_p} = 2 \times 10^{17}\ \mathrm{cm}^{-3}.$$

This value corresponds to hydrogen pressures over 6 Torr and is in a reasonable agreement with our experimental results.

On the other hand, the optimal hydrogen pressure for lasing at the 585.3 nm line is determined by the process of depopulation of the ULL ($2p_1$) through Penning ionization with hydrogen. When the rate of Penning reactions for this level is comparable to the rates of radiative and electron deexcitation the laser action begins to decrease. If we consider the estimated value for the Penning rate constant of the ULL ($2p_1$) [6] $k_p = 5 \times 10^{-10}$ cm^3/s, we see that it is about 2.5 times less than the rate constant for the $1s_2$ level. The hydrogen pressure at which Penning depopulation of the ULL becomes dominant should be about 2.5 times higher than the threshold pressure, i.e. 15 Torr. This is in a good agreement with our experimental results.

Concerning the hydrogen threshold pressure for laser action at the 1.15 μm line, it is lower than that for the yellow line – 4 Torr. In this case the depletion of the ($1s_2$) by Penning reactions leads to a lower population of the LLL ($2p_4$) which is excited by stepwise electron collisions. Because of the more complicated population inversion mechanism further investigations are necessary to explain the threshold and the optimal H_2 pressures.

5. Conclusions

A PPL operating at the NeI 585.3 nm and NeI 1.15 μm lines in Ne–H_2 mixture has been realized. A helical configuration of the electrodes was used. The dependence of the laser pulse shape and output power on current pulse duration and amplitude value were investigated. Peak output powers of 1.5 W for the yellow line and 1.2 W for the IR line has been measured.

The population inversion mechanism for the 585.3 nm line is discussed in the frames of a model for PPL. The main factor maintaining the population inversion for both lines is depopulation of the $Ne(1s_2)$ level by Penning reactions with H_2.

The simpleness of the laser tube design and the observed high values for the output power make this laser a promising device for practical realization.

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