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脉冲诱导放电气体激光器

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摘要：研究了一种实现新放电方法：诱导圆筒放电的可能性。该放电方法基于不同的粒子数反转机理，使用不同的原子和分子传能模式泵浦气体激光器。研制了用于气体中的脉冲诱导圆筒放电（脉冲感应耦合等离子体）激励系统，并对其进行了实验研究。首次实现了基于原子和分子不同传能模式的4种脉冲诱导激光器，其激励特性是光束发散角小，不同脉冲间的非稳定性在1%以内。首先研制出了基于F原子电子传能模式的红光激光器，这一激光器使用脉冲感应圆筒放电；通过在2.66～46.55 kPa气压下激励He-F_2（NF_3，SF_6）混合气获得了在624～755 nm波段的8种波长的输出；FI激光器的脉冲能量为2.6 mJ，脉冲持续时间为80 ns，光束发散角为0.4 mrad。同时研制出了基于基态CO_2分子传能的10.6 μm远红外激光器，该感应激光器在脉冲持续时间（FWHM）为160 μs时，获得的最大能量为152 mJ。另外，研制出了近远红外区的基于氢气分子中电子传能的脉冲感应放电氢气激光器，激射谱线为0.835，0.89，1.116和1.122 μm，脉冲持续时间为20 ns时获得的脉冲峰值功率为11 kW。最后成功研制了波长为337.1 nm和357.7 nm的基于自限制电子传能过程$C_u^3 \rightarrow B_g^3$的脉冲感应紫外氮气激光器，在低压为133 Pa的感应氮气激光器中获得的最大能量输出为4.5 mJ，峰值功率为300 kW，脉冲持续时间为（15±1）ns，测得的感应氮气激光器的光束发散角为0.3 mrad。

关　键　词：脉冲诱导圆筒放电；FI激光器；CO_2激光器；H_2激光器；N_2激光器；脉冲持续时间；环形激光束
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Pulsed inductive discharge gas lasers

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Abstract: The investigation results for the possibility of a pulsed inductive cylindrical discharge as a new method of pumping gas lasers operating at different transitions of atoms and molecules with different mechanisms of formation of inversion population are presented. The excitation systems of a pulsed inductive cylindrical discharge (pulsed inductively coupled plasma) in the gases are developed and experimentally investigated. At the first time, four kinds of pulsed inductive lasers on the different transitions of atoms and molecules are created. Characteristic features of the emission of pulsed inductive lasers are ring-shaped laser beam with low divergence and pulse-to-pulse instability is within 1%. Firstly, the red laser on the electronic transitions of atomic fluorine (FI) pumped by a pulsed inductive cylindrical discharge is developed. Lasing at 8 wavelengths in the spectral area 624－755 nm is obtained by exciting He-F_2(NF_3, SF_6) gas mixtures in a pressure range from 2.66－46.55 kPa. The energy of the FI laser is 2.6 mJ at pulse durations of 80 ns and the divergence is 0.4 mrad. Secondly,

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the far infrared laser on the vibrational-rotational transitions of CO_2 molecules in the ground electronic state with a wavelength of 10.6 μm is created. The maximum energy of this inductive laser is 152 mJ at the pulse duration of 160 μs (FWHM). Thirdly, the pulsed inductive discharge H_2 laser at the electronic transitions of hydrogen molecules in near IR laser is also developed. The laser action on four lines with 0.835 μm, 0.89 μm, 1.116 μm and 1.122 μm is obtained, and its pulsed peak power is 11 kW at duration of 20 ns. Furthermore, the pulsed inductive UV nitrogen laser on self-limited electronic transitions $C^3\Pi_u \rightarrow B^3\Pi_g$ at 337.1 nm and 357.7 nm is created, and its maximum generation energy is 4.5 mJ at low pressures 133 Pa and pulsed peak power is 300 kW at pulse duration (15±1) ns. The measured divergence of the inductive nitrogen laser radiation is 0.3 mrad.

Key words: pulsed inductive cylindrical discharge; FI laser; CO_2 laser; H_2 laser; N_2 lasers; pulse duration; ring shape laser beam

1 Introduction

The rf induction excitation of continuous-wave lasing was reported in Ref. [1-3]. Continuous-wave lasing on transitions in atomic argon ions in the green spectral range under excitation by a longitudinal inductive rf discharge was obtained in Ref. [1-2]. Lasing on vibrational-rotational transitions in CO_2 molecules in a wavelength range of 10.6 μm in an expanding nitrogen flow heated by an inductive discharge after the addition of cold CO_2 to it was reported in Ref. [3].

In this work, a method for exciting gas laser active media by a pulsed inductive cylindrical discharge is proposed and experimentally implemented in order to obtain lasing on electron transitions in atoms and molecules and vibrational-rotational transitions in molecules. It is important that the pulse repetition rate must be several hertz or higher; *i. e.*, all processes of discharge formation, creation of population inversion, amplification, absorption, and quenching must occur during each pulse irrespective of the past history of the preceding pulse.

It is well known that a pulsed transverse electric discharge as a method for pumping gas lasers has a number of advantages over a pulsed longitudinal or transverse discharge. Here, we assume that the pulsed transverse discharge is an electric discharge in which the current flows in a direction perpendicular to the optical axis. Such a discharge ensures lasing on a very large number of transitions in atoms, molecules, and their ions due to realization of various (including new) mechanisms of producing population inversion in a wide range of pressures including atmospheric pressure. This lasing is achieved because a much higher level of pulsed pumping power is ensured in the transverse discharge and, therefore, lasing occurs at various transitions, including those for which no gain can be obtained for other types of discharge. As a result, lasers with a high radiation energy and a high efficiency (1%-10%) can be developed.

In contrast to conventional pulsed longitudinal and transverse discharges, a pulsed inductive cylindrical discharge is formed due to the magnetic field induction produced by the pumping system without any electrodes in the active medium. An appropriate choice of the tube material may ensure the purity of the active medium considerable endurance of lasers. The formation of such a discharge is not accompanied by the appearance of cathode spots on the surface of the electrodes, which are responsible for the instability and contraction of the discharge, deterioration of the homogeneity of the discharge, contamination of the gas mixture, quenching of lasing, and limitation of the pulse repetition rate. The application of the pulsed inductive discharge for excitation is a promising method for pumping not only gas lasers, but also metal vapor and solid state lasers. In addition, this method can be used to produce the plasma for obtaining radiation (including induced radiation) in any spectral range, especially that extending from 100 nm to THz, which is of considerable interest for microelectronics, photolithography and biomedicine.

2 Apparatus

In our measurements, the spontaneous emission spectra of the inductive discharge in gases and the lasing spectrum were recorded with a Ocean Optics HR 2000 spectrometer, S-150 Solar LS spectrometer with a resolution of 0. 66 nm in the spectral range from 200 to 1100 nm and a SpectraPro-500 Acton Research Corp. spectrograph with a resolution of 0. 025 nm in the spectral range from 180 to 700 nm with different photodiodes and photomultipliers. The output laser energy was measured with a PE50-BB Ophir pyroelectric pulse energy meter (Ophir Optronics LtD.). The temporal parameters of electric pulses were recorded with high-voltage P6015A probes and a 200-MHz TDS-2024 Tektronix oscilloscope. The accuracy of measurements was 5%. The temporal parameters of optical pulses were recorded with a PhEC-22 and PhC-15 coaxial photocells with a temporal resolution of 10^{-10} s and infrared photodetector. The spatial distribution of the laser radiation intensity over the tube cross section and the light beam profile were analyzed by using a WinCamD-UCM digital video camera (Data Ray Inc.).

3 Experimental setup

The first excitation system we described is in Ref. [4-7]. A pulsed cylindrical inductive discharge in gases was created in our experiments by using an electrical circuit is shown in Fig. 1.

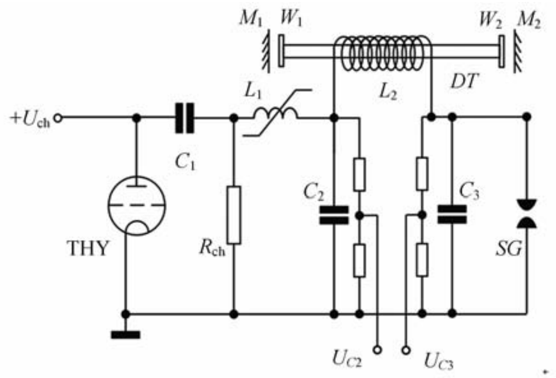

Fig. 1　Electric circuit of the pulsed inductive lasers with cylindrical discharge as a active volume. THY: thyratron TPI_1 $10k/50$, $C_1=80$ nF, $C_2=8$ nF, $C_3=18$ nF, L_1: choking-coil, L_2: inductor, DT: discharge tube, SG: self-triggered gas-filled spark gap

This excitation system differed from that described in Ref. [4-7] and provided more efficient energy transfer from a storage capacitor to the active medium[8]. To increase the voltage across an inductor and increase the energy input into gas, three capacitors was used in the circuit. The excitation system operated in the following way. The capacitor $C_1=80$ nF was charged from an ALE 152A Lambda EMI pulsed power supply up to the voltage 20-27 kV of the positive polarity. In this case, the energy of 15－30 J was stored. When the voltage across capacitor C_1 and achieved the maximum, a triggering pulse was fed to a high-voltage switch (TPI_1 $10k/50$ thyratron). After the thyratron actuation, the capacitor C_1 began to discharge, a negative voltage appeared across charging choking-coil L_1, and energy was transferred to capacitors C_2 and C_3. Both capacitors were charged during the time 1. 5-2. 0 μs up to the breakdown voltage of a spark gap. The capacitor C_3 and the spark gap represented a low-inductive circuit in which the capacitor C_3 began to discharge after the actuation of the spark gap slightly earlier than the capacitor C_2. During the discharge of the latter, a time-varying electric current passed through the inductor L_2 placed on discharge tube DT and creates varying magnetic field around it, which induces azimuthally electric current in gases, leading to break down and formation of a pulsed inductive discharge (pulsed inductively coupled plasma). Figure 2 shows the oscillograms U_{C_2} and U_{C_3} of voltage pulses across capacitors C_2 and C_3, respectively. These oscillograms were compared with oscillograms of spontaneous radiation pulses of the inductive discharge in gases I_{sp} and laser pulses I_{st}. By way of illustration in these experiments we are used nitrogen as a working gas[8]. One can see that, unlike electric-discharge nitrogen lasers, the onset of pulsed lasing I_{sp} does not coincide in time with the onset of the spontaneous emission pulse I_{sp}. Lasing appears and proceeds during the time period corresponding to the maximum voltage gradient across the capacitor C_2. The spontaneous emission I_{sp} also appears during this time period, but 60—70 ns earlier than lasing and its duration is 3—4 times longer. By analysing the obtained oscillograms, we concluded that the first small maximum in the spontaneous emission oscillogram I_{sp} is explained by the appearance of a capacitive discharge in nitrogen at the inner surface of the tube.

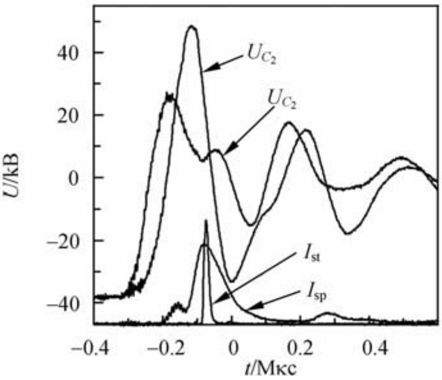

Fig. 2 Oscillograms of voltage pulses across capacitors C_2 and C_3 and spontaneous emission pulses I_{sp} of the inductive discharge plasma in nitrogen and nitrogen laser pulses I_{st}. $U_{ch}=25$ kV

After 50—60 ns, the inductive discharge was ignited and the main spontaneous UV emission peak (with the maximum amplitude and duration) of nitrogen appeared simultaneously, which corresponded to the appearance and development of the inductive discharge in the discharge tube. In our opinion, the oscillogram of the main spontaneous emission peak I_{sp} reflects the shape of the inductive discharge current pulse in nitrogen. The inductive and capacitive discharges further developed simultaneously in time until the end of the inductive discharge. The capacitive discharge existed during the entire recharging time of the capacitor C_2 and, therefore, during the existence of alternating current in the inductor L_2. Under pressures below 133.3 Pa, inductive discharge filled the discharge tube completely, uniformly and high intensity. As the mixture pressure increased above 133.3 Pa, the intensity of inductive discharge in the center of the tube rapidly decreased. The discharge started to assume cylindrical form and concentrated near the inner tube wall surface. According to our observations discharge thickness decreased as a function of pressure. During the discharge of the latter, an alternating current flowed through an inductor L_2, which produced an inductive discharge in the discharge tube. The ignition moment of the inductive discharge was determined by the appearance of spontaneous emission of gases in the discharge tube. It was found in Ref. [6-8] that the output energy of the inductive lasers was proportional to the discharge tube diameter, i. e. the lasing efficiency and output energy increased with increasing the tube diameter. Because of this, we used in our experiments a ceramic discharge tube with inner diameter of 42 mm and external diameter of 50 mm. The tube was sealed by means of plane-parallel windows oriented perpendicular or at the Brewster angle to the tube axis (Fig. 1). The optical resonator was formed by external plane dielectric mirrors. The rear dielectric mirror had the reflectance 99% in the selected spectral region. The reflectance of the output mirror was optimized during experiments to obtain the maximum output energy. Mirrors with reflectance from 8% to 93% were used. The inductor L_2 consisted of separate sections representing solenoids made of a cable wire of cross section 1.5－6 mm^2. The results presented in this paper were obtained by using the inductor containing 30 sections, each of them consisting of four coils. The solenoids were connected in parallel, and the total length (～68 cm) of the inductor was assumed the length of the active medium of the gas laser. Gases or its mixtures were admitted from a gas system into the tube up to pressures 13.3 Pa-133 kPa. Gases flowed longitudinally during experiments.

4 Results

4.1 Red laser on the electronic transitions of atomic fluorine

In our first experiments to demonstrate the possibility of the creation of the pulsed inductive gas laser, we chose transitions in neutral fluorine atoms which works by the excitation of the pulsed cylindrical inductive discharge in a He : F_2 (NF_3) mixture, because the population inversion in these transitions is reached at comparatively low excitation levels in a wide pressure range. In this case, a high gain is achieved, which ensures superluminescence regime in a low-*Q* resonator, and lasing takes place in the red spectral region and the transition from spontaneous emission to the lasing mode is easily detected.

There are many works on lasing on various transitions in fluorine atoms in a spectral range of 623－780 nm[9-25]. Lasing was observed on 16 lines. However, owing to different excitation conditions, the spectra obtained in different works differ in the number of lines with various wavelengths. Population inversion on atomic fluorine transitions was created using two methods of excitation, namely, a longitudinal electric discharge[9-13] in low-pressure (66.5—6 650 Pa) helium mixtures with fluorine-containing molecules and a transverse electric discharge[14,16-17,19] ensuring lasing in the same mixtures in a wide pressure range up to 300 kPa. At low pressures, HF, SF_6, CF_4, C_2F_6, NF_3, and F_2 molecules were used as fluorine donors, while only NF_3 and F_2 molecules were used for high pressures due to the homogeneity of the discharge achieved using the preliminary UV ionization of the discharge gap. In most available experiments, lasing on transitions in fluorine atoms took place in the superluminescence regime. The duration of laser pulses in various experiments varied from a few microseconds (in a longitudinal electric discharge) to tens of nanoseconds (in a transverse electric discharge). The gas mixture forming the active medium of the laser usually consisted of helium and admixtures of fluorine-containing molecules in a ratio of 30 : 1 to 1 000 : 1. Helium was required for creating inversion on transitions in fluorine atoms via excited states of helium atoms. The use of other inert gases (such as Ne or Ar) as the buffer gas did not lead to lasing. The above features of the operation of the FI laser indicate that it is a suitable device for obtaining lasing in a pulsed cylindrical inductive discharge. In this work the laser on the electron excited transition of fluorine (FI) atoms pumped by a pulsed inductive cylindrical discharge is developed. Lasing at 8 wavelengths (Fig. 3) is obtained by exciting He-F_2(NF_3) gas mixtures in a pressure range from 20 to 350 Tor. The results of experimental investigation of the spectral, temporal, and energy characteristics of the inductive FI laser are obtained.

At the ends of the discharge tube, adjusting units with plane-parallel CaF_2 plates W_1 and W_2 were fixed. On one side of the tube, a plane Al mirror or dielectric mirror M_1 with reflection 99 % in red spectral area was placed. We studied the intensity and duration of radiation emitted by the pulsed inductive discharge, as well as its spectral and energy characteristics under various

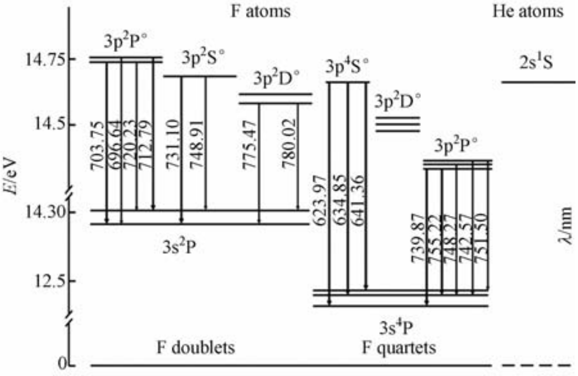

Fig. 3 Energy level diagram for transition in FI. The 16 possible laser transitions of an FI laser at the doublet and quartet states. Solid lines designate the laser transitions that are observed in this work.

excitation conditions. As the active medium for the FI laser, we chose He : F_2 (NF_3) gas mixtures of various compositions under various pressures. The charging voltage U_C was varied from 20 to 27 kV. The best results were obtained under the maximal voltage U=27 kV; the total inductance of inductor L was equal to 60 nH in this case. Under low pressures of the He : F_2 gas mixture in the pressure range from 133 to 532 Pa, the inductive cylindrical discharge filled the tube almost uniformly over the cross section, but no lasing was achieved. An increase in pressure from 0.532 to 2.66 kPa led to a redistribution of the discharge from the center to the tube walls, and a ring-shaped discharge was observed. Under pressures of the He : F_2 gas mixture from 2.66 to 46.55 kPa, lasing on electronic transitions in fluorine atoms was obtained in the wavelength range 624—755 nm. Laser beam was shaped in the form of a ring with an outer diameter of 3 cm and an inner diameter of about 2.6 cm. Thus, the active volume for a 60-cm-long inductor was 110 cm^3. The energy of laser radiation was depended from the ratio of the mixture components and total pressure. The investigation of dependence of the spectral lines intensity of FI laser on the total gas mixture for different He : F_2 ratio is obtained. The optimal composition for our pumping conditions was He : F_2 (80 : 1) and total pressure 5.32—6.65 kPa. When F_2 was replaced by NF_3, lasing was also obtained, but with a lower intensity. For this reason, subsequent experiments were made on the He : F_2 (80 : 1) mixtures. Maximum energy of FI laser in these experiments was achieved 2.6 mJ at pulse power 30 kW and durations 80 ns. The divergence was 0.4 mrad[4].

4.2 Far infrared laser on the vibrational-rotational transitions of CO_2 molecules

The purpose of this part of paper is to study the ability of the pulsed inductive cylindrical discharge to be a new method for pumping laser media and for creating the population inversion at vibrational-rotational transitions of molecules (such as CO_2, HF(DF) in the ground electronic state. In our experiments, we used CO_2 : N_2 : He gas mixture as an active laser medium for the CO_2 laser. The main purpose of our experiments was to investigate the temporal, energy, and spatial characteristics of pulsed inductive CO_2 laser for gas mixtures with a different ratio of components as a function of the total pressure and excitation parameters. Our final goal was to obtain pulsed generation regime at vibrational-rotational transitions of CO_2 molecules ground electronic state in the IR spectral region at a wavelength of 10.6 μm and to create pulsed inductive CO_2 laser.

During the last decade CO_2 lasers were widely used in medicine, environmental monitoring, and material processing. In recent years CO_2 lasers with a power of 5—20 W have found numerous applications in medicine, for example in such fields as dentistry, plastic surgery, dermatology, and gynecology.

The inversion formation mechanism in the CO_2 laser is based on electronic excitation of the vibrational-rotational levels of CO_2 and N_2 molecules in the ground electronic state[26]. The scheme of low vibrational levels of the ground electronic state Σ_g^+ of CO_2 molecules and the state

$X^1\Sigma_g^+$ of N_2 molecules is shown in Fig. 1[27]. In this case, the population of these levels is determined not only by the collisions with electrons but also by the relaxation of CO_2 molecules from higher states to the ground state.

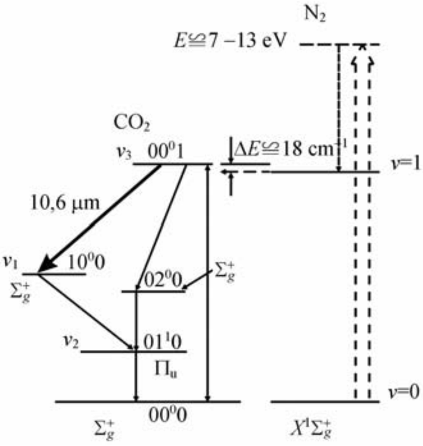

Fig. 4 Scheme of low vibrational levels of the ground electronic state Σ_g^+ of CO_2 molecules and the ground electronic state $X^1\Sigma_g^+$ of N_2 molecules

The other process of population of the upper laser level is resonant energy transfer from vibrationally excited N_2 molecules. Since there is a small difference in the energies ($\Delta E = 18$ cm^{-1}) between level 00^01 of the CO_2 molecule and level $X^1\Sigma_g^+ (v = 1)$ of the N_2 molecule, this process is very efficient. In the ground electronic state, other higher vibrational levels of N_2 molecules are also almost in resonance with the corresponding levels of CO_2 molecules ($\Delta E < kT$) up to level 00^04, and the transitions from these excited vibrational levels to laser level 00^01 take place with a high rate.

Two excitation methods, namely, longitudinal and transverse pulsed electric discharges, are usually used to obtain pulsed generation in a CO_2 laser with a wavelength of 10.6 μm[27]. Such excitation methods are associated with certain technical difficulties, such as temperature increase, which destroys the population inversion at the vibrational-rotational transitions of CO_2 molecules at operation in the pulse-periodic regime with high repetition rate. Typically pulsed electric discharges are created between metallic electrodes. This process is accompanied by electrode material sputtering leading to pollution of the active medium, by the appearance of cathode spots, by the formation of streamers leading to degradation of laser radiation homogeneity and stability, and by changes of gas mixture composition. As a result, laser lifetime decreases, that requires replacing not only the working gas, but also the electrodes and optical elements of the laser cavity.

In this study, the excitation system of the cylindrical pulsed inductive discharge in the $CO_2 : N_2 : He$ gas mixture is developed.

Under pressures below 133 Pa, inductive discharge filled the discharge tube completely. As the mixture pressure increased above 133 Pa, the intensity of inductive charge in the center of the tube rapidly decreased. The discharge started to assume cylindrical form and concentrated near the inner tube wall surface. According to our observations discharge thickness decreased as a function of pressure. Under pressures corresponding to CO_2 laser generation regime discharge thickness was in the range of 5 – 6 mm. Discharge thickness estimations were based on generation ring thickness which was measured using thermopaper.

Various numbers of sections coiled by an insulated stranded wire with a cross-section of 1.5 mm^2 to 4 mm^2 were used in the solenoid. The number of coils in each section varied from 8 to 16. The length of the solenoid determined the length of the active medium and constituted 60 – 66 cm. Glass and ceramic tubes with different inner diameters in the range of 20—42 mm were used in these experiments. It was found that the higher the tube diameter, the higher the emission radiation intensity. Maximum radiation intensity was obtained with the help of inductor containing 32 sections with 6 turns each, in the tube with 42 mm inner diameter, and gas mixture of under pressure of 2.0 kPa.

The tube is sealed by two plane-parallel KCl windows located perpendicularly to the tube axis at the ends. Planar dielectric and Au mirrors are placed on the outer side near the windows. The rear Au mirror has a reflection coefficient of 90% at the wavelength $\lambda=10.6$ μm, whereas the output dielectric mirror is changed in the process of the experiment using mirrors with a reflection coefficient in the range of 20%—80%. The output mirror reflection was optimized to achieve the maximum generation energy and is approximately 50%.

Under total pressures of 1.33—2.0 kPa of the gas mixture $CO_2 : N_2 : He - 1 : 4 : 12$ lasing on vibrational-rotational transitions of CO_2 molecules at a wavelength of 10.6 μm, a pulsed inductive discharge has been observed. The maximum generation energy 152 mJ is obtained in a ceramic tube with an inner diameter of 42 mm in the $CO_2 : N_2 : He - 1 : 4 : 12$ gas mixture at a pressure of 15—2.0 kPa and the maximum charging voltage of 27 kV. The maximum efficiency in these first experiments did not exceed 0.3%. The measured divergence of CO_2 laser radiation is 8 mrad.

The possibility of the inductive discharge CO_2 laser operation in the pulse-periodic regime is analyzed in the experiments. The pulse repetition rate varies from 1 to 50 Hz. It is revealed that the average radiation power increases linearly with the pulse repetition rate. Thus, an average power of 3.0 W is obtained at a repetition rate of 50 Hz and generation energy of 60 mJ. The reproducibility of the amplitude from pulse to pulse is equal to about ±3%.

To understand the time behavior of the laser radiation and the excitation pulse, we investigated spontaneous radiation of the inductive discharge in the $CO_2 : N2 : He$ mixture in the spectral region from 0.2 μm to 1.0 μm. In these experiments, all mirrors were removed from the cavity and the KCl windows were replaced by quartz ones. The spontaneous spectrum was recorded by an S-150 spectrometer (SOLAR). Almost all radiation was found to be concentrated in the range from 0.3 to 0.4 μm. Interpretation of the spectrum shows that it corresponds to the second positive system of bands of the $C^3\Pi_u \rightarrow B^3\Pi_g$ transition of nitrogen molecules and is identical to the spectrum obtained in nitrogen laser. The radiative lifetime of nitrogen molecules at the upper level $C^3\Pi_u$ is known to be $\tau_C \approx 38$ ns and is mainly determined by the transition to the lower level $B^3\Pi_g$ with the lifetime $\tau_B \approx 9.1$ μs[28]. The transition from level $B^3\Pi_g$ is possible only to level $A^3\Sigma_u^+$. Then, relaxation to the ground electronic level $A^3\Sigma_u^+$ of the nitrogen molecule takes place[29-32]. Hence, major energy of the inductive discharge is used to excite nitrogen molecules to electronic levels $C^3\Pi_u$ and $B^3\Pi_g$. This can explain a delay (of about 10 μs) in the appearance of the IR generation pulse and indicates that in these conditions direct excitation of the upper laser level 00^01 of CO_2 molecules by the discharge electrons does not take place. It occurs only as a result of energy transfer from vibrationally excited nitrogen molecules at the ground electronic level $X^1\Sigma_g^+$. Therefore, to increase the efficiency of the CO_2 laser in further experiments it is necessary to optimize the excitation parameters of the active medium by an inductive discharge.

4.3 Near infrared laser on the electronic transitions of the H_2 molecules

There are several works on lasing on the electronic transitions in H_2 molecules in near IR spectra region[33-34]. Lasing was observed on 7 lines. Maximum peak power 1.5 kW was obtained.

The purpose of the given experiments was to obtain the pulsed inductive discharge in diatomic molecular gases with the parameters required for the inversion population formation on the electronic levels of molecules such as $2s\sigma^1\Sigma_g^+(E)\rightarrow(2ps)^{21}\Sigma_g^+(B)$ transitions of hydrogen molecules and to achieve the laser action with wavelength at spectral area 0.8－1.1 μm (Fig. 5).

Lasing on the electronic transitions of H_2 molecules in near IR spectra region with excitation by pulsed inductive discharge is reported. The generation was observed on 4 lines. The wavelength $\lambda_1=0.835$ μm (band (2,1) rotational line $P(2)$, $\lambda_2=0.89$ μm (band (1,0) rotational line $P(2)$, $\lambda_3=1.116$ μm (band (0,0) rotational line $P(4)$, the $\lambda_4=1.122$ μm (band (0,0) rotational line $P(2)$ that corresponds to $2s\sigma^1\Sigma_g^+(E)\rightarrow(2ps)^{21}\Sigma_g^+(B)$ transition. Maximum of laser emission peak power was at two lines: 7 kW for wavelength $\lambda_2=0.89$ μm and 5 kW for wavelength $\lambda_4=1.122$ μm, respectively. Peak power of the lines $\lambda_1=0.835$ μm and $\lambda_3=1.116$ μm was match weaker. Pulse duration of generation was 18－20 ns (FWHM). Laser is working both on one wavelength and on two wavelengths simultaneously with competition between these transitions. The active medium was hydrogen at optimal pressure 66.5－106 Pa.

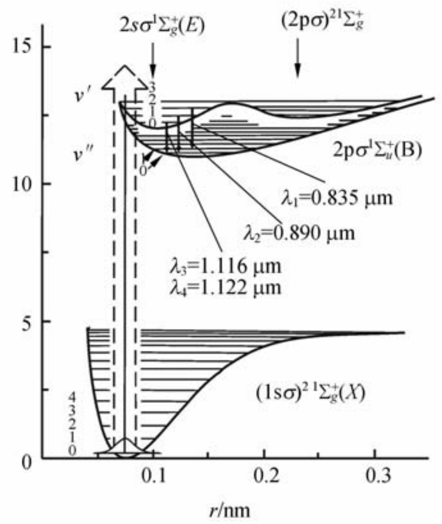

Fig. 5　Potential energy curves for hydrogen molecules

4.4　Ultraviolet laser on the self-limiting electronic transitions of the N_2 molecules

There are many works on lasing on self-limited transitions of the N_2 molecules[35-37]. Lasing was observed in a spectral range of 315－380 nm on the different bands of the $C^3\Pi_u\rightarrow B^3\Pi_g$ transition in molecular nitrogen.

The purpose of this part of paper is to study the ability of the pulse periodic inductive cylindrical discharge to be a new method for pumping laser on self-limited electronic excited transitions of molecules and atoms (such as N_2, H_2, He, metal vapor).

The aim of this paper is to show that a pulsed inductive discharge is an efficient alternative tool for exciting UV nitrogen lasers, offering a number of advantages compared to transverse and longitudinal electric discharges. The results of experimental studies of spectral, temporal, spatial and energy parameters of the UV radiation of an inductive nitrogen laser are presented. Lasing in molecular nitrogen at 337.1 nm is usually obtained by exciting nitrogen and its mixtures with other gases with the help of longitudinal and transverse pulsed electric discharges. Although upon excitation of small active volumes (up to 10 cm^3), the output energy is low (0.1－0.2 mJ), it is possible to fabricate lasers with high pulse repetition rates, up to 10 kHz and above. By using a transverse discharge to excite a nitrogen laser, it is possible to increase the active volume up to 30－100 cm^3. The output energy of such lasers is considerably higher and can achieve 10 mJ and more. The operating pressure of pure nitrogen in these lasers is 2.66－6.65 kPa, while in the mixtures of nitrogen with other gases (He, Ar, SF_6, NF_3, *etc.*) this pressure is from 13.3 kPa to several hundred kPa. This leads to technical difficulties in the development of excitation systems that should provide a homogeneous volume discharge in nitrogen used as the active medium of the laser. The parameters of the discharge strongly affect the output power and duration of laser pulses, the lasing stability and the operating life of the gas medium. The formation mechanism of inductive discharge is of interest because in this case there are no certain concepts about the parameter E/p ($E=U/d$, where U is the voltage applied to electrodes between which the discharge is produced; d is the distance between electrodes; and p is the pressure of nitrogen[31], which plays a key role in the development of electric discharge nitrogen laser. Therefore, the investigation of pulsed UV inductive nitrogen lasers is of current interest. The properties of the UV nitrogen laser have been studied in many papers[28-31, 36-37].

The inversion formation mechanism at the $C^3\Pi_u \rightarrow B^3\Pi_g$ transition in molecular nitrogen is well studied and described in Ref. [28-30] as shown in Fig. 6.

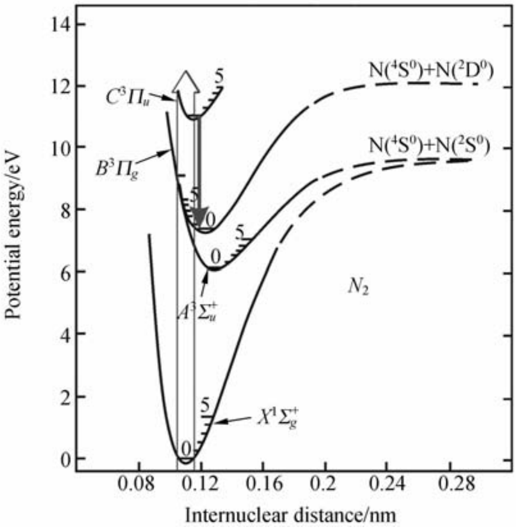

Fig. 6 Potential energy curves for nitrogen molecules

It involves the direct electron-impact excitation of molecules from the $X^1\Sigma_u^+$ ground state during which the predominant population of the upper working levels occurs in accordance with the Franck ë Condon principle. The radiative lifetime of a nitrogen molecule on the $C^3\Pi_u$ upper laser level is $\tau_C \sim 38$ ns[32] ($\tau_C \ll \tau_B$) and is determined mainly by the transition to $B^3\Pi_g$ the lower laser level with the lifetime $\tau_B \approx 9$ μs[32]. The radiative transition from the $B^3\Pi_g$ level can occur only on the metastable $A^3\Sigma_u^+$ level. Therefore, under normal conditions, the depopulation rate of the $B^3\Pi_g$ level due to collisions of nitrogen molecules with other particles is comparatively small, and stationary inversion cannot be achieved at the $C^3\Pi_u \rightarrow B^3\Pi_g$ transition. The inversion can be obtained only in the nonstationary regime at the excitation pulse front under the condition that the excitation rate of the upper level is higher than that of the lower level. Such transitions are called self-contained transitions. To produce a homogeneous volume electric discharge and obtain lasing at the transitions of the second positive band system of molecular nitrogen in nitrogen lasers described in the literature, the condition $E/p \geqslant 200$ V cm^{-1} Pa^{-1} should be fulfilled[31]. Because electrodes are absent in the case of the inductive discharge, the parameter E/p becomes uncertain. However, the general concept of UV nitrogen lasers was assumed invariable, and it was necessary to produce the inductively coupled plasma with electronic parameters providing the inversion mechanism described above, namely, to obtain electrons in plasma with concentration $10^{14}-10^{15}$ cm^{-3} and energy 12−16 eV[38].

Experiments with the pulsed inductive discharge in nitrogen showed that the pressure range in which the inductively coupled plasma can exist is quite narrow, from 13.3 to 1330 Pa. Visual observations with the use of different optical filters showed that the inductive discharge was homogeneous in the entire pressure range. No sparks and streamers were observed in the inductive discharge in pure nitrogen and its mixtures. At minimal nitrogen pressures (lower than 13.3 Pa), the inductive discharge almost completely filled the discharge tube over the entire inductor length and the tube cross section. As the nitrogen pressure was further increased (above 26.6 Pa), the emission intensity of the inductive discharge in the central part of the tube began to decrease rapidly. The discharge took a cylindrical shape and concentrated near the inner wall of the tube. The discharge was observed in the form of a luminous cylinder with the walls of thickness decreasing with increasing pressure. At nitrogen pressures exceeding 532 Pa, the discharge emission intensity decreased, and at a pressure of ~1.33 kPa the inductive discharge abruptly terminated. At the inner surface of the discharge tube, a weakly emitting electric discharge was detected which we considered as a capacitive discharge. The spontaneous emission spectrum of the pulsed inductive discharge plasma in nitrogen was studied in the absence of resonator mirrors with sealing windows oriented at an angle to the tube axis close to the Brewster angle. The spectrum shows that all the emission lines are concentrated in the second positive system of bands of molecular nitrogen in the spectral range from 300 to 400 nm (Fig. 7).

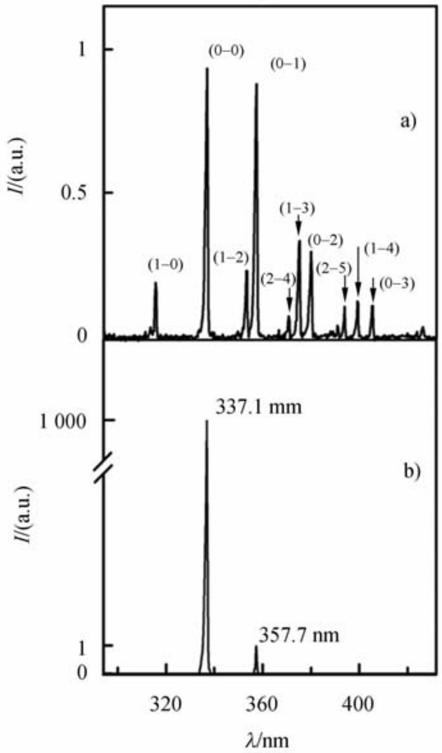

Fig. 7　Spontaneous emission spectrum of the inductive discharge in nitrogen (a) and emission spectrum of the inductive nitrogen laser (b)

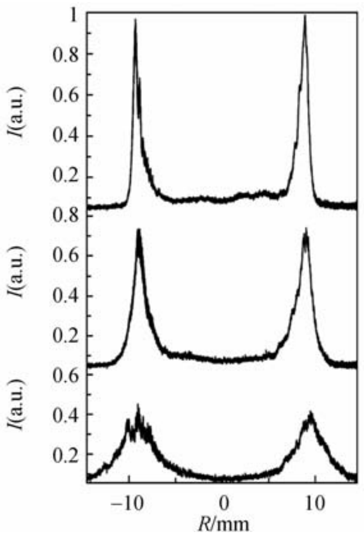

Fig. 8　Profile of the laser beam of inductive discharge nitrogen laser on the distance 0.1 m, 4 m and 8 m from output window

The ratio of band intensities in the spectrum depended on the nitrogen pressure. At pressures 26.6—400 Pa, the two most intense lines were observed at 337.1 nm (0-0 band) and 357.7 nm (0-1) band) Fig. 7, f. After the mounting of dielectric mirrors and alignment of the optical resonator, we obtained UV lasing at transitions of molecular nitrogen excited by the pulsed inductive discharge in the pressure range from 40—400 Pa. The maximum of the lasing efficiency was achieved at pressures 66.5—106 Pa. Investigations of the vibrational structure of the emission spectrum of the nitrogen laser showed that, unlike the results obtained in Ref. [7], lasing was observed not at one but at two lines corresponding to two most intense spontaneous emission lines at 337.1 nm (0-0 band) and 357.7 nm (0-0 band) Fig. 7(b). Unlike the spontaneous spectrum, the intensity ratio for these lines proved to be rather high. The intensity of the 337.1 nm line exceeded that of the 357.7 nm line more than by two orders of magnitude. It is interesting that simultaneous lasing at these two lines in pure nitrogen at low pressures (133—266 Pa) was previously reported only in one paper[39]. In experiments[39], nitrogen was excited by a longitudinal electric discharge of duration 1.5 μs in a tube of length 90 cm with the inner diameter 3 mm. Only the laser emission spectrum was studied, and the energy and temporal parameters of laser emission were not reported. The results obtained in Ref. [39] proved to be useful for our investigations and we used them to interpret the rotational structure of the emission spectra of the inductive nitrogen laser in the (0-0) and (0-1) bands because we have failed to record the detailed rotational structure of these lines due to a low spectral resolution of our spectrometers. The widths of the 337.1 nm and 357.7 nm lines were measured to be 4 ∶ 5 A. According to Ref. [39], we found that the laser emission spectrum in the (0-0) band contained 32 lines related to 46 rotational transitions (mainly in the *P* branch) with wavelengths from 336.6912 to 337.1437 nm. Emission in the (0-1) band is caused by the 12 rotational transitions of the *P* band and consists of four lines with wavelengths from 357.6112 to 357.695 nm. We studied the temporal dependences of excitation, spontaneous and inductive nitrogen laser pulses. Fig. 2 shows the oscillograms U_{C_2} and U_{C_3} of voltage pulses across capacitors C_2 and C_3, respectively. To increase the output energy of the inductive nitrogen laser compared to that obtained in Ref. [7], we optimized the resonator *Q* factor. The maximum output energy 4.5 mJ is achieved for R_2=60 %. The laser pulse FWHM was (15±1) ns. As the reflectance of the output mirror was further increased, the output energy decreased. However, the laser pulse duration increased from (13±1) ns for R_2=16% to (18±1) ns for R_2=93 %. This is larger than in electric-discharge lasers, where the pulse duration does not exceed 5－10 ns[36-37]. The duration of UV laser pulses (at the base level) in the dense resonator exceeded 35 ns. During the measurements of the output energy at different charging voltages, the nitrogen pressure was optimized for each voltage. As the charging voltage was increased from 20 to 27 kV, the optimal pressure increased from 66.5 to 106 Pa. The maximum energy of 4.5 mJ was obtained at the maximum voltage of 27 kV. For 15 ns pulses, this corresponds to the laser pulse power of 300 kW. It is important to note that such a high pulsed power was never achieved before in a nitrogen laser at low pressures 133 Pa. This result demonstrates the specific features of the operation of the inductive nitrogen laser such as its emission spectrum containing many vibrational lines, which is obtained upon such excitation, and a long duration of pulses with a comparatively flat leading edge (about 7 ns). The total lasing efficiency, obtained as the ratio of the output energy at the maximum voltage to the energy stored in the capacitor C_1, was about 0.05%. According to our measurements, the pulse-to-pulse instability of the lasing amplitude was 1 %. By using a digital video camera, we studied the spatial distribution of the laser radiation intensity at the discharge tube output. The light-beam cross section had the shape of a ring of external diameter ～ 34 mm.

The study of the beam profile showed that the laser radiation intensity at the external boundary of the ring was minimal Fig. 8. The lasing intensity increased towards the ring centre and achieved the maximum at a distance of about 1 mm from the external boundary. Then, the radiation intensity decreased almost to zero at a distance of 4 mm from the boundary. This value can be treated as the ring width. The laser radiation divergence, which was determined by measuring the size of the laser radiation ring at different distances from the laser 0.1 m to 8 m and was ～ 0,3 mrad. The circular structure of the beam cross section is a specific feature of pulsed inductive lasers with a cylindrical inductive discharge. Such beams in the case of a low radiation divergence offer certain advantages because they can be focused to produce the radiation intensity distribution similarly to Bessel beams. We performed experiments with the inductive nitrogen laser operating in the repetitively pulsed regime. The pulse repetition rate was varied from 1 to 30 Hz. We found that the average output power increased linearly with increasing pulse repetition rate. For the repetition rate of 30 Hz and output power of the nitrogen laser of 4 mJ, the average output power was 120 mW. The output energy was independent of the pulse repetition rate because the active medium was cooled at the ceramic tube wall directly adjacent to the lasing region.

5 Conclusions

A pulsed inductive cylindrical discharge as a new method of pumping gas lasers operating at different transitions of atoms and molecules with different mechanisms of formation of inversion population are proposed and experimentally realized. The excitation systems of a pulsed inductive cylindrical discharge (pulsed inductively coupled plasma) in the gases are developed and experimentally investigated. At the first time four kinds of pulsed inductive lasers on the different transitions of atoms and molecules are created. Characteristic features of the emission of pulsed inductive lasers are ring-shaped laser beam with low divergence and pulse-to-pulse instability is within 1%. A red laser on the electronic transitions of atomic fluorine (FI) pumped by a pulsed inductive cylindrical discharge is developed. The lasing at 8 wavelengths in the spectral area 624—755 nm is obtained by exciting He-F_2(NF_3, SF_6) gas mixtures in a pressure range of 2.66—46.55 kPa. The energy of the FI laser is 2.6 mJ at pulse durations of 80 ns and the divergence is 0.4 mrad. A far infrared laser on the vibrational-rotational transitions of CO_2 molecules in the ground electronic state with a wavelength of 10.6 μm has been created. The maximum energy of this inductive laser is 152 mJ at the pulse duration of the laser emission about 160 μs (FWHM). At the first time, the pulsed inductive discharge H_2 laser at the electronic transitions of hydrogen molecules in near IR laser has been developed. The laser action on four lines with 0.835, 0.89, 1.116 and 1.122 μm is obtained and its pulsed peak power is 11 kW at duration of 20 ns. The pulsed inductive UV nitrogen laser on self-limited electronic transitions at the $C^3\Pi_u \rightarrow B^3\Pi_g$ transition in molecular nitrogen at 337.1 nm and 357.7 nm is also created. The maximum generation energy 4.5 mJ from inductive N_2 lasers only at low pressures 133 Pa is achieved, its pulsed peak power is 300 kW at pulse duration of (15±1) ns. The divergence of the inductive nitrogen laser radiation is measured to be 0.3 mrad

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●**下期预告**

振动干扰下光路失调数值计算

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为了实现振动干扰下光路失调数值的精确计算,从而为燃烧诊断光学系统中机械振动对光学性能的影响提供预测评价方法,利用ANSYS有限元分析软件建立了光学振动失调物理模型,通过瞬态动力学分析得到了反射镜在振动激励下的位移响应。基于矩阵光学、几何光学理论和机械振动理论,分析了反射镜的振动失调光束传输变换矩阵,建立了振动失调光路传输理论模型,推导出了振动激励下光路失调数值计算方法,并通过实验对该计算方法进行了验证。实验结果表明,水平和垂直方向的仿真计算结果与实验测试结果的相对误差分别为4.1%和0.8%,该计算方法具有很高的精度。