High-voltage pulse generators for effective pumping of super-atmospheric pressure CO₂-lasers

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Abstract. This work is devoted to describing of constructions and main characteristics of some types compact pulse generators with amplitude of voltage pulses up to 200 kV, rise-times about 10 ns and pulse energy per pulse up to 20 J. For reduction of rise-time of high-voltage pulses were used spark-discharge two electrodes commutators (sharpeners) at working pressures up to 100 atm.

1. Introduction

Effective excitation of super-atmospheric pressure volume discharges, pumping of CO₂-lasers at super-atmospheric pressures and effective generation of “runaway electrons” can be realized by using of very high voltage pulses with nanosecond rise times [1, 2]. Many types of pumping generators for excitation of gas lasers working at high pressures described in [3].

The excitation of gas lasers of atmospheric and superatmospheric pressures are realized in a self-sustained volume discharge plasma. To obtain of such types of discharges in dense gases must be fulfilled a number of strict conditions:

- create a sufficiently high level of initial ionization \(N_0 \geq 10^7–10^9 \text{ cm}^{-3}\) before the breakdown of the discharge gap;
- to ensure a sufficiently rapid increase of the voltage on the discharge gap;
- reduce the duration of the volume discharge current to values that are less than the development time of the fastest plasma instability [4, 5].

The preliminary ionization of gases in the interelectrode gap in CO₂-laser mixtures at atmospheric pressure is quite simply and efficiently realized by vacuum ultraviolet radiation (VUV-radiation) of auxiliary spark discharges [6]. However, with an increase of the working pressure from one atmosphere to 10–15 atm the efficiency of preionization by VUV-radiation strongly decreases due to the very highly absorption of ionizing radiation by carbon dioxide molecules [6, 7]. Under these conditions it is advisable to use soft X-rays which can be generated in the working gas in the plasma of auxiliary spark or surface discharges as a result of inhibition of "runaway electrons" [1, 2].

The rise time of the voltage across the discharge gap should be significantly less than the time of electron drift through the discharge gap. Otherwise during the rise of the voltage to the level of breakdown in the discharge gap the initial free electrons created at the preliminary ionization stage will disappear and the discharge will begin to develop from the background level and spark channels will be formed in the gap instead of a volume discharge [8]. Therefore as a quantitative criterion for
the duration of the rise time of a high voltage pulse we can take the electron drift time through the gas-discharge gap as a characteristic time for this gaseous medium. For gas-discharge gaps with \( d_{AC} = 1–2 \text{ cm} \) (typical values for small-sized TEA-CO₂ lasers) and characteristic values of electron drift velocity \( V \sim 10^8 \text{ cm} \cdot \text{s}^{-1} \) the rise time of the high voltage pulse will be \( \sim 10–20 \text{ ns} \).

The life-time duration of the volume discharge or the volume discharge current duration is limited by the development time of plasma instabilities and for the fastest of them such as explosive emission of electrons the characteristic development time corresponds to the electron drift time through the discharge gap [9–11].

Thus to obtain volume discharges in dense gases it is necessary to form voltage pulses with an amplitude sufficient for gap breakdown and the rise time significantly less than the time of electron drift through the gap. In addition pulsed generators those produce such voltage pulses must ensure the duration of the current through the gap at the level of the electron drift time through the gap. For example – realization of electrical breakdown in interelectrode gap with \( d_{AC} = 1 \text{ cm} \) in CO₂-laser mixture at total pressure \( P_{\Sigma} = 10 \text{ atm} \) pulse generator must be generates pulses with amplitude up to 200 kV with a rise time about \( \tau \sim 10–20 \text{ ns} \).

The present work is devoted to describing construction of some types compact pulse generators with amplitude of voltage pulses up to 200 kV, rise-times about 10 ns and pulse energy per pulse up to 20 J.

2. Pulse generators

The main types of high-voltage pulse generators which very often used for pumping CO₂-lasers at atmospheric and super atmospheric pressures are generators without multiplication of initial voltage and generators with voltage multiplication. The first category includes generators with a direct discharge of storage capacitors in the gap through the switch. The magnitude of the voltage pulses and time parameters (rise time and duration) are determined by the parameters of the switch and electrical circuit. Maximal amplitude high voltage pulses in that category of generators not exceed the charge voltage. The second category of pulse generators includes Marx generators, inverse LC-generators and pulse transformers [11, 12]. The transition from working pressures in one atmosphere to pressures in several atmospheres leads to a proportional increase in the breakdown voltage and accordingly to form voltage pulses with the required amplitude and more shorter rise time and total duration. Therefore pulse generators without voltage multiplication as well as with voltage doubling (LC-generators) find their application for CO₂-lasers operating at pressures of 2–3 atm and enough small interelectrode gaps.

In conditions where the operating pressures reach 10 atm obtaining volume discharges is possible only when using pulse generators with voltage multiplication such as Marx generators and pulse transformers.

2.1. Marx generators

The structure of the Marx generators is such that the "last" switch breaks under high overvoltage and its switch-on time have the minimum value among of all switches. Therefore the voltage rise time on the load (gas-discharge gap) will be determined by the switching time of this switch. Typical switching time for high voltage (up to 25–35 kV) hydrogen thyratrons and pseudo-sparks have time intervals between 20–50 ns. At the overvoltages the time of switching is reduced and can reach 10 ns.

The magnitude of the voltage pulse produced by the Marx generator is determined by the number of stages. Since all the storage capacitors of the Marx generator after the operation of all the switches are turned on in series the total capacity which is discharged to the gas-discharge gap in "n" times less than the individual capacity in each stage. The discharge time of such small total storage capacitor even if there is a noticeable inductance of the discharge circuit will have a small value. For example, when the total capacity of the Marx generator is \( C_{\Sigma} = 375 \text{ pF} \) (individual capacitance \( C_{H} = 3 \text{ nF} \) and the number of stages \( n = 8 \)) with the total inductance \( L = 0.5 \mu \text{H} \) the discharge current duration will be about \( \tau \sim 40 \text{ nanoseconds} \). For reduce of the pumping current duration along the discharge gap low-
Inductive "peaking" capacitors are installed. They are charging from the Marx generator and after reaching the breakdown voltage discharged to the gas gap in the minimum time.

Marx generators provide the formation of high voltage pulses with amplitudes up to several megavolts with switching time for tens of nanoseconds at total energy in hundreds of kilojoules [11, 12].

An eight-stage Marx generator with air spark commutators was created to pump of small-sized sealed-off super-atmospheric pressure CO₂-laser for work in the monopulse mode. The pseudo-spark of TP11-10k/50 type was used as a triggered switch in the first stage. Storage capacitors in each stage were made from ceramics capacitors K15-4 type with a capacity in each stage from 3 to 4.4 nF. The charge voltage of the storage capacitors could reach values up to 30 kV. The maximum voltage achieved by such generator reached 200 kV with the duration of the rise time at a resistive load of about 10 nanoseconds. The maximum value of accumulated energy in storage capacitors reached 20 J.

Application of switching elements in the Marx generators in the form of air spark commutators does not allow to use of such generators for pumping of gas lasers at pulse repetition rates more than a few Hz. Many practical applications require laser pulses at pulse repetition rates at hundreds or thousands Hz.

![Figure 1. Scheme of two-stage Marx generator with pulsed hydrogen thyratrons as switches: \( T_1, T_2 \) - thyratrons TG11-1000/25; \( C_1, C_2 \) - storage capacitors; \( C_p \) - peaking capacitors; \( L_1-L_5 \) - inductances; \( Tr \) - heating transformer of thyratron \( T_1 \); \( PTr \) - "potential" heating transformer of thyratron \( T_2 \).](image)

For a significant increase of the pulse repetition rate of Marx generators as switching elements should be used pulsed hydrogen thyratrons or pseudo-spark switches (thyratrons with cold cathode). The scheme of one of these generators (two-stage Marx generator) is shown on figure 1.

The thyratron \( T_1 \) of the first stage of the Marx generator is started from the triggering generator. The second thyratron \( T_2 \) of the high-voltage stage is started from a positive pulse, which is automatically formed by the divider \( R_1-R_2 \) immediately after the operation of the thyratron \( T_1 \). After both thyratrons have started on the \( L_2-L_4 \) - inductances a high voltage pulse of negative polarity with an amplitude of \( 2U_0 \) will be formed. The duration of the rise-time of the voltage pulse formed in the two-stage Marx generators is determined by the switching time of the second thyratron \( T_2 \) which is triggered under double potential. The forming time of high current discharge in the thyratron \( T_2 \) under
such conditions is reduced compared to the forming time of the arc discharge in the thyratron \( T_1 \). This time as shown by the results of studies reaches 10 ns.

Heating of the cathode and the hydrogen generator at the second thyratron \( T_2 \) must be realized under the potential of up to 25 kV. For thyratrons of the TGI1-1000/25 type the heating current is 25 A. For pseudo-spark commutators the currents in the heaters of hydrogen generators do not exceed 5 A. For the three-stage Marx generator heating of the cathode and hydrogen generator should be realized under the potential of 50 kV. "Potential" transformers that can be used for these purposes are very cumbersome and have significant mass. As the voltage (number of cascades) increases the weight and dimensions of the “potential” transformers for each successive stage will only increase. So Marx generators for work in a pulse-periodic mode must be limited by two stages. In this case the maximum values of pulse voltage with a short rise-time are limited to values of 50–60 kV. With the presence of a peaking condensators on the active element of the laser the voltage of its electrodes can be in \( \approx 1.5–1.8 \) times exceed the voltage produced by the Marx generator [11, 12].

2.2. Pulse transformers

More convenient and flexible generators from the point of view of simplicity of a design and convenience in work at formation of high-voltage impulses especially in a pulse-periodical mode are pulse transformers. These generators use only one switch, one pulse transformer and two capacitors.

Pulse transformers allow to form voltage pulses that can exceed the initial level not only several times, but also several ten times. The scheme of the generator based on the pulse transformer is shown on figure 2. One of the capacitors – \( C_0 \) – performs the function of the storage element, the second – \( C_1 \) – the peaking capacitor. For effective energy transfer from storage capacitor into peaking capacitor there must be the next interrelation:

\[
C_2 = \frac{C_1}{n^2}
\]  

where \( n \) – transformation coefficient.

The equation (1) is an analytical expression of limit connection the total energy transfer from the storage capacitor \( C_0 \) to the peaking one \( C_1 \).

As a switch \( S \) a pulsed hydrogen thyratrons or a pseudo-spark gap can be used.

At the direct connection of the peaking capacitor to the electrodes for ignition of the volume discharge the charge time of the peaking capacitor \( C_1 \) will correspond to the duration of the rise-time of the voltage pulse. Its duration can be estimated by Thomson’s ratio [12, 13]:

\[
\tau = \frac{T}{4} \left( LC_2 \right)^{1/2}
\]  

where \( L \) – scattering inductance of the pulse transformer; \( T \) – oscillation period in the \((LC_1)\) circuit.

![Figure 2](image-url)
For a pulse transformers with a closed magnetic core based on ferrite rings the duration of the rise-time achieve $\tau \sim 50$ ns at the best. In transformers with an open magnetic core the duration of the forward voltage front reaches several microseconds.

For a significant reduction in the duration of the forward front of high-voltage pulses in the generators based on pulse transformers high-speed spark discharge sharpeners can be used and they must install in series with the peaking capacitor. In figure 2 such sharpener is indicated by the SSG symbol. Sharpeners are uncontrolled spark gaps with operating pressures up to 100 atm. The characteristic response times of such sharpeners are 2 nanoseconds or less [14].

Exterior form of metal-ceramic spark sharpeners of the RO-50 type is shown in figure 3. Industrial sharpeners of this type are designed for operating voltages of 180–260 kV with the maximum switched energy per pulse is up to 8 J at maximum currents of up to 1 kA. The maximum frequency of operation of these sharpeners does not exceed 50 Hz [14].

During the studies of super-atmospheric pressure CO$_2$-lasers pumping conditions the magnitude variation of voltage pulses applied to the electrodes for the volume discharge forming was transformed by changing of the operating voltage of the spark sharpeners. They were filled with working gases to certain pressures at which the operating voltage had the following series of values: 80, 100, 120, 140, 160, 180 and 200 kV. Pulse transformer, sharpening capacitors and spark sharpeners were mounted in one tank filled transformer oil. Such arrangement provided sufficient compactness to the entire high-voltage pulsed generator.

For a significant increase in the average electric power inject into the plasma of a pulse-periodical TE-CO$_2$ laser a new high-voltage pulse generator was created on the base of two pulsed transformers $PT_1$ and $PT_2$ with closed magnetic conductors. Its electrical circuit is shown on figure 4.

The closed magnetic circuits were made from ferrite rings of the 125×80×12-000-HH type. The primary windings of these transformers were connected with two individual storage capacitors $C_1$ and $C_2$, which are switched by a single thyratron ($T$). In some cases switching of the storage capacitors $C_1$ and $C_2$ were made using two individual thyratrons which were started simultaneously.

Capacitive energy storage capacitors $C_1$ and $C_2$ were collected from ceramic capacitors of the KVI3-4700pFx12xV type. The values of capacitances $C_1$ and $C_2$ were varied from 10 to 25 nF and storage energy for one pulse in these conditions changed from 4 to 10 J. The secondary windings are connected sequentially. The transformation coefficient of each transformer was equal to $k = 5$. This value of the transformation coefficient was a compromise between the voltage multiplication, duration of the rise-time high-voltage pulses and the efficiency of energy transfer from pulse generator to the volume discharge plasma. The form of the magnetic circuits and transformer windings is shown in figure 5.
Figure 4. The electrical scheme of pulse generator on the base of two pulse transformers: $PT_1$, $PT_2$ – pulse transformers; $C_1$, $C_2$ – storage capacitors; $C_{P1}$, $C_{P2}$ – peaking capacitors; $L_1$, $L_2$ – inductances; $SSG$ – spark sharpener; $D$, $MT$ – resistive voltage divider and measuring current transformer; $A$, $C$ – electrodes for volume discharge ignition.

Figure 5. The form of a high-voltage pulse generator based on two pulse transformers.

This high-voltage pulse generator was successfully used for pumping CO$_2$ lasers of atmospheric and superatmospheric pressures in both monopulse and pulse-periodical modes at pulse repetition rates up to 5 kHz. In the monopulse mode to shorten the duration of the rise-time of high-voltage pulses was used spark sharpeners. In the pulse-periodical mode some reduction in the duration of the rise-time of high voltage pulses was provided by a decrease in the capacitance of the primary storage capacitors.

3. Pumping of CO$_2$ lasers at atmospheric and super-atmospheric pressures
Two-stage Marx generators using pulsed hydrogen thyatrons of the TGI1-1000/25 type as switches were used to pumping of TE-CO$_2$ laser at pulse repetition rates up to 2 kHz at a total pressure of working mixtures up to 5 atm. Volume discharge was ignited in the interelectrode gap with dimensions $V' = 28 \times 1.6 \times 0.8$ cm$^3$. The working mixtures consisted of CO$_2$:N$_2$:He in ratios from 1:1:6 to 1:1:10. At a pressure of one atmosphere the composition of the working mixtures could be enriched with molecular components and the ratio between CO$_2$:N$_2$:He could have values from 1:1:4 to 1:1:3.
At pulse repetition rates below 500 Hz, the ratios between the components of the CO$_2$:N$_2$:He operating mixtures could reach values from 1:1:2 to 2:1:2. The predominance of carbon dioxide concentrations over molecular nitrogen in the working mixtures ensures the formation of laser pulses without a characteristic "tail" with a duration of up to 20 ns at half-height.

As the pressure of the CO$_2$:N$_2$:He working mixtures increased the helium content had to be increased. This is due to the fact that with increasing pressure the breakdown voltage of the gas-discharge gap in which the formation of the volume discharge also increases. The insert of helium into the mixture reduces the breakdown voltage and at an operating pressure of 5 atm in CO$_2$:N$_2$:He mixtures = 1:1:8–1:1:10 the breakdown voltage for the interelectrode gap $d = 1.6$ cm is $U \approx 52–46$ kV. Such voltages are provided by a two-stage Marx generator using as a switch pulsed hydrogen thyatrons TGI1-1000/25 type. The pumping energy densities at the maximum pulse repetition rates in CO$_2$ laser mixtures at super-atmospheric pressure depending on the component composition and reached values of 80–120 mJ·cm$^{-3}$·atm$^{-1}$.

Pulse generator the scheme of which is shown in figure 4 was used to pump TE-CO$_2$ lasers with volumes of active media (excitation zones of the volume discharge) $V_1 = 7 \times 0.8 \times 0.8$ cm$^3$ and $V_2 = 18 \times 0.8 \times 0.8$ cm$^3$ in the monopulse mode at total pressures of the working mixtures of CO$_2$:N$_2$:He up to 10 atm and provided a pump energy density of up to 200 mJ·cm$^{-3}$·atm$^{-1}$.

Preliminary ionization in all TE-CO$_2$ lasers was realized by vacuum ultraviolet radiation from spark or sliding discharges which were located in not far of the main discharge gap.

The study of the generation characteristics of TE-CO$_2$ lasers showed that increasing the operating pressure of CO$_2$-laser mixtures to 10 atm and reducing the length of the optical resonator to 20 cm provides the formation of laser pulses with durations at half-height of 5–7 ns with a pulse energy of up to 130 mJ.

4. Conclusion

The basic requirements to the parameters of high-voltage pulses which can provide effective formation of self-sustained volume discharges in CO$_2$-laser mixtures at super-atmospheric pressures are formulated. The main types of generators that are able to provide the formation of the necessary parameters of pumping pulses in both monopulse and pulse-periodic modes are considered.

A new approach to the creation of effective pumping generators for super-atmospheric CO$_2$-lasers with amplitude of the pulse voltage up to 200 kV with rise-time less than 20 ns and duration of the pump current up to 20–30 ns were grounded and realized. It consists in the use of high-speed spark sharpeners in high-voltage generators based on pulse transformers.

A variant of a pumping generator based on two pulse transformers is considered which provides the formation of volume pumping discharges in CO$_2$-laser mixtures at a total pressure up to 10 atmospheres with a pumping energy density up to 200 mJ·cm$^{-3}$·atm$^{-1}$ and the generation of laser pulses in a small-sized TE-CO$_2$ laser with a resonator length of 20 cm with a duration of 5–7 nanoseconds at half-height and a pulse energy of up to 130 mJ.

It was demonstrated the possibility of applying a two-stage Marx generator using pulsed hydrogen thyatrons as switches for the purpose of effective pumping TE-CO$_2$ laser in pulse-periodical regime with pulse repetition rates up to 2 kHz with pumping energy density up to 80–120 mJ·cm$^{-3}$·atm$^{-1}$.

References

[1] 2014 Runaway electrons preionized diffuse discharges ed V F Tarasenko (New York: Nova Publishers) p 598
[2] Kulakov S L, Kuchinsky A A, Maslennikov A G et al 1990 Volumetric self-discharge with pre-ionization by UV and soft X-rays J. Tech. Phys. 60 43
[3] Khomich V Yu, Yamschikov V A 2015 Foundations of electro–discharge excitation systems for CO$_2$, N$_2$ and F$_2$ lasers (Moscow: Fizmatlit) p 168
[4] Raizer Yu P 2009 Gas discharge physics (Dolgoprudny: Intellekt) p 736
[5] Mesyats G A, Osipov V V and Tarasenko V F 1991 Pulsed gas lasers (Moscow: Nauka) p 272
[6] 1986 Gas lasers ed I Mc Daniel and W Nigan (Moscow: Mir) p 552
[7] McDaniel E W 1967 Collision phenomena in ionized gases (Moscow: Mir) p 832
[8] Karnyushin V N and Soloukhin R N 1981 Macroscopic and molecular processes in gas lasers (Moscow: Atomizdat) p 200
[9] Mesyats G A 1993 Ectons chapter 1 (Ekaterinburg: Nauka) p 184
[10] Korolev Yu D and Mesyats G A 1982 Field emission and explosive processes in a gas discharge (Novosibirsk: Nauka) p 260
[11] Mesyats G A 2004 Pulse energy and electronics (Moscow: Nauka) p 704
[12] Mesyats G A 1974 Generation of powerful nanosecond pulses (Moscow: Soviet radio) p 256
[13] Vdovin S S 1991 Design of pulse transformers (Leningrad: Energoatomizdat) p 208
[14] http://plasmalabs.ru/ Spark Gaps (Sharpeners).