*Quantum Electronics* **32** (6) 506 – 510 (2002)

PACS numbers: 42.55.Ks; 42.60.Lh
DOI: 10.1070/QE2002v032n06ABEH002232

# Scaling of repetitively pulsed electric-discharge wide-aperture lasers

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*Abstract*. **The main reasons that hamper an increase in the energy and average output power of wide-aperture electric-discharge lasers are analysed. The physical and technical requirements imposed on the laser chamber design and a pump source of the laser for the attainment of high technical characteristics are formulated. A laser design is proposed, which involves separate, electrically uncoupled modules arranged along the optical axis. A new design of the electrode unit underlies the working principle of the laser chamber of an individual module, wherein both electrodes are made of sets of plates electrically insulated from each other and connected to the common busbars of the pump source via stabilising inductors. Technical efficiencies of 3.5 % and 2.4 % for specific energy outputs of 4.2 and 2.9 J $L^{-1}$, respectively, were obtained in HF and DF chemical lasers with the above electrode units and electrode gaps of 12 cm. A design of wide-aperture electric-discharge lasers based on carrying cylindrical shells was proposed.**

***Keywords***: *electric-discharge laser, scaling, discharge stabilisation, HF(DF) laser.*

## 1. Introduction

Several papers have reported the investigation of wide-aperture electric-discharge lasers operating in a single-pulse regime, such as nonchain chemical HF(DF) lasers [1], $CO_2$ lasers [2, 3], and excimer XeCl lasers [4, 5]. Similar lasers can also be designed for operating in a repetitively pulsed regime (see, for instance, Ref. [6]). Producing a transverse gas flow in this case will inevitably involve changing the discharge gap geometry and the position of the pump source. This will most likely result in a deterioration of the output laser parameters. The development of wide-aperture repetitively pulsed electric-discharge lasers (RPEDLs) is restrained by the complexity of physical and technical problems arising in their design. In addition, the wide-aperture RPEDL design concept to allow a relatively simple scaling of the parameters for these lasers is absent.

Consider the main reasons that hinder an increase in the energy and average output power in wide-aperture RPEDLs. The output energy can be increased by increasing the discharge gap aperture and, accordingly, the pump energy per unit active length of the laser. This leads to an increase in the dimensions of the capacitive energy storage of a pump source and in its moving away from the centre of the discharge gap. As a result, the inductance of the discharge circuit increases, thereby increasing the discharge duration, which often causes the development of instabilities in the discharge plasma. Difficulties also arise in the matching of the increasing wave impedance of the pump source with the plasma impedance of the volume discharge. The mismatch makes the period of energy input into the discharge plasma still longer. As a result, spark breakdowns of the discharge gap may also occur during the second half-wave of the voltage pulse. The spark gap breakdowns reduce the service life of the electrode system and induce strong local temperature nonuniformities on the electrode surfaces. An increase in the interelectrode gap should be accompanied by an increase in the energy of the pump source and a nearly proportional rise in its voltage. As a result, the load on the switches in the laser power supply circuit increases.

The output laser energy can also be increased by increasing the discharge length. Sometimes this involves sectioning the discharge gap. In this case, the ratio $L_{\text{las}}/L_{\text{in}}$ increases, where $L_{\text{las}}$ is the laser size along the optical axis and $L_{\text{in}}$ is the total length of the discharge gap. The laser length is limited by the internal losses in its active medium.

Additional difficulties arise on passing to the repetitively pulsed regime of a wide-aperture electric-discharge laser. They are primarily related to the formation of the flow of the gas medium in the discharge gap and to the location of the laser pump source. In this case, the duration of the stable phase of the volume discharge becomes shorter owing to the development of near-electrode perturbations and gas density perturbations in the working volume.

## 2. Conceptual approaches to the design of wide-aperture RPEDLs

Several approaches to the problem of producing wide-aperture lasers were proposed in Refs [7, 8]. Initially [7], a new design of the electrode unit was proposed, in which each of the electrodes is made of a set of plates electrically insulated from each other and connected to the common busbars of the pump source via stabilising inductors. This design was tested employing the active medium of an electric-discharge chemical HF laser [9, 10]. The experi-

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Received 27 February 2002
*Kvantovaya Elektronika* **32** (6) 506 – 510 (2002)
Translated by E.N. Ragozin

ments showed that a stable volume discharge was produced for a different height of the interelectrode gap, and a high specific energy outputs and lasing efficiency were realised. Note that the segmentary design of one of the KrF(XeCl)-laser electrodes with an inductive stabilisation was first proposed in Ref. [11].

The development of a RPEDL with a large volume of the active medium and high performance characteristics requires the fulfilment of several, generally well-known physical and technical requirements. Among them are: the realisation of highest specific energy output and lasing efficiency; the minimisation of the voltages of electrical devices employed in the laser; shortening the duration of the discharge current pulse; lowering the energy deposition in an accidental spark breakdown of the discharge gap; lowering the circulation velocity and the gas flow rate in the working gap; reducing the distance between the electrodes of the neighbouring sections when sectioning the laser in its length; the employment of electrodes of simple design; the production of a stable discharge in a wide working-medium composition range with moderate requirements on the precision of electrode mounting; the realisation of reasonably simple designs of current conductors, the gas circuit, the laser chamber, and the pump source; and minimising the intensity of scattered electromagnetic radiation and reducing the laser weight and dimensions. The fulfilment of the above-listed conditions in the development of wide-aperture lasers on the basis of presently known RPEDL designs involves certain difficulties.

Consider the feasibility of meeting these requirements in a laser with plate electrodes and an inductive discharge stabilisation. This laser exhibits a significantly improved discharge stability and also a reduced energy release upon an accidental spark breakdown of the discharge gap. This is accomplished by employing stabilising inductors, which limit a fast local build-up of the discharge current density. The laser allows producing the gas flow through the plate electrodes. In this case, the capacitors of the storage capacitor of the laser can be located at a minimal distance to the discharge gap on both its sides (the lead-in current conductors have a minimal size in this design). Such a location of the pump source is impossible with the use of continuous electrodes in a laser with a transverse circulation of the active medium. A similar arrangement of the pump source is used to obtain high performance characteristics in lasers without a gas flow (see, for instance, Refs [2, 6]). Therefore, a gas-flow laser with plate electrodes admits an ultimate reduction of discharge inductance.

In a laser with continuous electrodes, the discharge gap length is shorter than the length of the electrode because its ends are rounded off. For a plate electrode, the length of the discharge gap is equal to the distance between its extreme plates. When the discharge gap is sectioned, reducing the spacing between the neighbouring sections induces the breakdown between the electrodes of the neighbouring sections. The consequences of this breakdown are significantly less serious in the case of plate electrodes due to the stabilising conductors.

In a laser where the working medium circulates through the plate electrodes, the gas replacement factor may be close to unity (the gas heated in the interelectrode gap has to be almost completely replaced after every pulse), whereas in a usual circulation system it is quite often equal to 2 – 3. The plate electrodes produce a uniform flow of the gas medium. In combination with the side walls of the laser chamber, they can efficiently damp the acoustic perturbations in the active laser medium.

Consider the main design approaches which can be applied for scaling electric-discharge lasers with plate structures. The modular approach proposed in Refs [7, 8] underlies the design of a wide-aperture laser. The approach involves making a laser of separate, completely independent modules that are closely arranged along the optical laser axis. The design of a repetitively pulsed $CO_2$ laser involving separate, electrically uncoupled modules was also proposed in Ref. [12] indicating the indisputable advantages of this approach. When employing plate electrodes, the module length is nearly equal to the length of its discharge gap.

The modules operate independently and are accommodated in a common housing. The module incorporates a separate pump source section and a section of the electrode system of its own. The pump sources of separate modules are united in a common laser pump source only by means of the timing and charging system. In this case, the task of developing the laser reduces to the elaboration of a single module from the viewpoint of its design, electrical engineering, discharge stability, and efficiency. This reduces the expenses significantly and shortens the time taken to develop the laser. We emphasise that optimising the module is a many-aspect task.

Among the possible ways of realising the modular approach is designing a RPEDL with a large volume of the active medium with the use of carrying cylindrical shells [8].

Fig. 1 shows a schematic diagram of the module of a wide-aperture RPEDL with plate electrodes on the basis of cylindrical shells [7, 8]. The main units and systems of the laser module are accommodated inside a carrying shell (*1*). The pump source section consists of two parts, each of which being enclosed in its own dielectric shell (*2*). Placed between these dielectric shells is the plate electrode unit (*3*) connected to the sections of the pump source via current

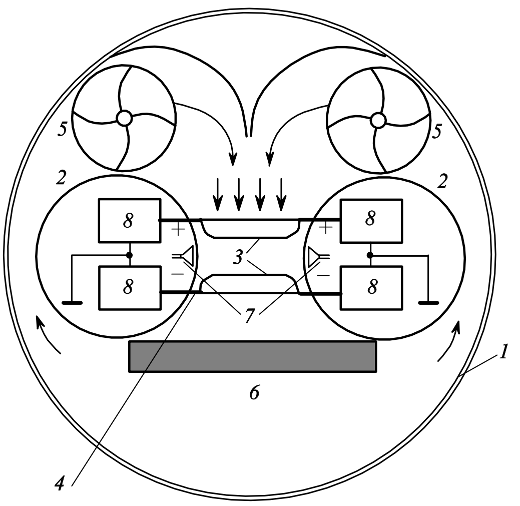


**Figure 1.** Cross section of the module of a wide-aperture RPEDL with a high average output power: (*1*) carrying shell; (*2*) dielectric shells; (*3*) plate electrodes; (*4*) current conductors; (*5*) diametrical ventilators; (*6*) heat exchanger; (*7*) X-ray sources; (*8*) pulsed voltage generator; the arrows indicate the flow direction.

conductors (*4*), which pass through the dielectric shells. The gas flows perpendicular to the working electrode surfaces. The gas circulation is effected by ventilators (*5*), e.g. of the diametrical type. This kind of circulation allows lowering the gas replacement factor to about unity and reducing the power of the circulation-driving device. The working gas is cooled in a heat exchanger (*6*).

This design solution affords the minimal possible inductance of the connection of the pump sources to the laser electrodes. As a result, the period of energy input shortens, and the discharge stability and the laser efficiency improve. It is significant that the approach under discussion allows the energy module characteristics at the elaboration stage to be optimised employing a section of the pump source located only on one side of the discharge gap. If the pump source consists of two thus optimised sections located on either side of the discharge gap, the output energy of a separate module can be raised practically two-fold. In this case, the discharge width should be doubled in comparison with the one-sided version through the use of electrodes with a wider working part. This approach significantly simplifies and makes cheaper the design elaboration, investigation, and optimisation of the module.

The laser electrodes transparent for the gas flow are a set of relatively thin plates electrically insulated from each other. The plates are uniformly spaced throughout the electrode length. Each of the electrode plates is connected, via its inductive element inside the chamber to a segment of the common busbar of this electrode. The working edge profile along the plate length is selected in such a way as to obtain the requisite transverse uniformity of energy release in the discharge. The plate electrode design makes it possible to minimise (down to several centimetres) the separation between the electrode systems of the neighbouring modules, which is hard to attain with the use of continuous electrodes. The application of high-technology plate electrodes in combination with inductive stabilisation allows us to significantly relax the requirements on precision of their mounting, improve the immunity to spark production, and reduce the energy release in a spark.

In some cases it is expedient to take advantage of a bipolar pulsed voltage generator (PVG) as the PVG for every part of a pump source section. Using this PVG permits a reduction of the intensity of electric field between the structural elements of the laser and its electrodes. Preference is given to a PVG involving circuits with $LC$ inverters. The voltage across the electrodes exceeds the charging voltage by a factor $2N$, where $N$ is the number of $LC$ inverters in the PVG. To obtain a steep edge of the pulse of voltage across the discharge gap, use can be made of a peaking gap.

To improve the electrical safety of the laser and attenuate the scattered electromagnetic radiation, the shell (*1*) is either made all-metal, or made of a dielectric covered by a metal. This improves the compatibility of the laser with other electrical-engineering devices.

To uniformly preionise the active volume, X-ray sources (*7*) can be used. They can be placed at equal distances from both electrodes, near the side walls of dielectric chambers (*2*) in the vicinity of the 'ground' potential of the PVG or behind the plate electrodes, which are transparent enough for X-rays. It is expedient to apply the master oscillator–amplifier system to attain a high directivity of the laser radiation for long active laser lengths.

In our opinion, these design principles can be used in the development of chemical, excimer, and $CO_2$ lasers (particularly, lasers operating at high pressures of the active medium), and probably electric-discharge oxygen–iodine lasers.

## 3. Experimental realisation of a wide-aperture laser

The above approaches were realised in the development of a nonchain electric-discharge HF(DF) laser. The wide-aperture laser was investigated employing a working chamber made of a glass-reinforced plastic tube with an internal diameter of 300 mm. The electrode unit consisted of two plate 100-mm wide electrodes fixed inside the chamber using lead-in current conductors. The electrode separation was 120 mm. The electrode plates were made of 1-mm thick copper sheets; the working surfaces of the plates were profiled to ensure the requisite discharge width. The electrode plates were insulated from each other and were located uniformly along the optical axis at intervals of 7 mm. The total length of the discharge gap was ~ 300 mm. Each of the electrode plates was connected to the common busbar of the electrode pump source with the aid of a ~ 1 μH stabilising inductor.

At the end flanges of the discharge chamber, $CaF_2$ plates were located. An external resonator consisting of two dielectric mirrors was used. The chamber was evacuated to a pressure of 0.1 Torr and filled with a working mixture of $SF_6$ with $H_2(D_2)$.

The electrical circuit of the laser is given in Fig. 2. A bipolar PVG of the laser pump source on the basis of a circuit with two $LC$ inverters and a peaking gap in the ground circuit was arranged on one side of the discharge gap. The PVG made use of 100-kV pulsed KMK-100-0.05 capacitors with a capacitance of 50 nF ($C_1 - C_4$). The capacitors were charged to a voltage $U_0 = 40 - 80$ kV from a VS-0.1-100 high-voltage static rectifier. To lower the inductance of the discharge circuit and improve the safety and reliability in operation of the electrical circuit, the capacitors and the gaps were enclosed in a metal housing filled with transformer oil. On actuation of the gaps (*1*) and (*2*), in ~ 3 μs the capacitors $C_1$ and $C_4$ recharge and the voltage across the peaking gaps (*3*) and (*4*) attains its maximum value equal to $\sim 2U_0$. The capacitance of the shock discharge circuit was 12.5 nF. Several hundred nanoseconds prior to the recharge of capacitors $C_1$ and $C_4$, the peaking gaps are turned on and a voltage $\sim 4U_0$ with a short rise time is applied across the working gap.

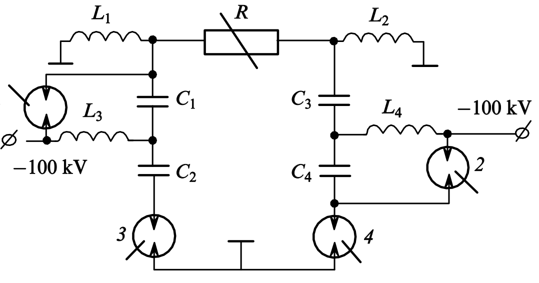
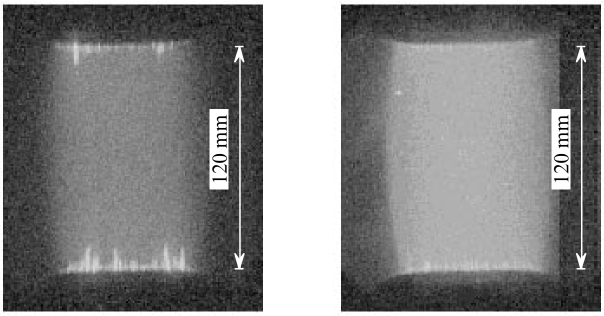


**Figure 2.** Electrical circuit of the laser PVG: ($C_1 - C_4$) storage capacitors; ($L_1$, $L_2$) charging inductances; ($L_3$, $L_4$) uncoupling inductances; (*1*–*4*) controlled gaps; ($R$) active load.

Therefore, only one stage of storage capacitors was employed to pump the laser unlike Ref. [1], where three stages were used with a peaking gap between the second and third stages.

Fig. 3 shows photographs of the discharge emission in the working chamber for a gas pressure of $\sim 0.1$ atm and a charging voltage $U_0 = 50$ kV. The volume nature of the discharge is evident. The discharge width is approximately 8.5 cm. When pure $SF_6$ is used as the working gas (Fig. 3a), streamers are easily observable near the electrodes. Lowering the pump energy leads to a significant reduction of the dimensions of the streamers and their glow intensity. In the active medium of a chemical laser ($SF_6 : H_2 = 10 : 1$) the streamers are in fact absent (Fig. 3b), which testifies to a higher discharge stability in the presence of hydrogen in the working mixture. The possibility of producing a volume discharge in pure $SF_6$ is indicative of an extremely high stability of the discharge with inductive stabilisation. At the same time, wide-aperture discharges with continuous electrodes without preionisation exhibit a volume character only in the presence of hydrocarbons as donors of hydrogen [1]. When approximately a quarter of the plates were tilted in such a way that the separation of the corresponding plates varied by 0.5 – 0.7 mm across the width of the discharge gap, the discharge retained stability and the output laser parameters did not change. This serves to illustrate the relaxed requirements on the precision of mounting the electrode plates.



a b

**Figure 3.** Photographs of the discharge emission when employing $SF_6$ (a) and a mixture of composition $SF_6 : H_2 = 10 : 1$ (b) as a working gas.

Typical pulse shapes of the discharge current and the voltage across the working gap are given in Fig. 4a. The time dependences of the energy inputted into discharge and the active discharge resistance are shown in Fig. 4b. About 60 % – 65 % of the energy accumulated in the storage capacitors is inputted into discharge. The discharge retains its volume nature for a charging voltage of capacitive storage devices up to 80 kV. A further increase in $U_0$ results in a mismatch of the wave impedance of the pump source and the active resistance of the plasma and is responsible for the occurrence of through spark columns during the second half-wave of the voltage pulse.

For a working mixture with an $SF_6 : H_2 = 10 : 1$ composition at a total pressure of 84 Torr, we obtained an output energy of 13.4 J for an efficiency of 3.5 %. For an $SF_6 : D_2 = 10 : 1$ composition mixture at a total pressure of 70 Torr, the energy was 9.2 J for an efficiency of 2.4 %. With the employment of one more PVG located on the other side of the discharge gap and an increase in discharge width up to $\sim 14 - 17$ cm, the output laser energy can be increased by about a factor of two.

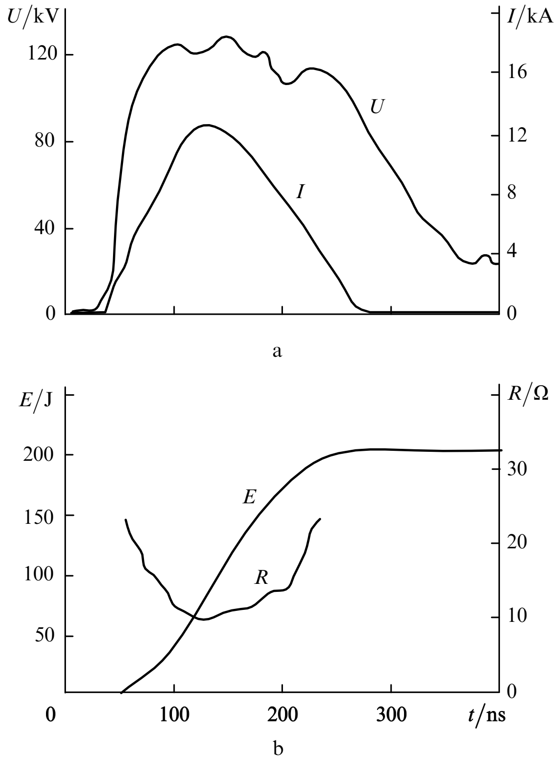


**Figure 4.** Typical time dependences of the discharge current $I$, the voltage across the discharge gap $U$, the discharge resistance $R$, and the energy $E$ supplied into the discharge.

The above-outlined design of a wide-aperture electric discharge laser underlay the production and subsequent testing of a laser operating in the repetitively pulsed regime. The laser consisted of three modules arranged in series in which the gas mixture streamed through the plate electrodes. The wide-aperture HF laser with a pulse repetition rate of 10 Hz passed through a test successfully. Therefore, the operating capacity of the proposed concept was confirmed in the repetitively pulsed regime, thereby laying a foundation for its further development.

## 4. Conclusions

A concept of designing wide-aperture electric-discharge lasers was proposed, making it possible to eliminate the problems arising in their scaling up. A consistent application of this concept will allow a considerable reduction of temporal and material expenses on the development of RPEDLs and most likely ensure the attainment of requisite output laser parameters. The principle of modular laser design, the employment of plate electrodes, and the inductive discharge stabilisation underlie this concept. This concept is most amply realised when the gas circulation is effected through the electrodes and use is made of cylindrical carrying shells in the accommodation of the devices of the laser. The proposed concept of a wide-aperture electric-discharge laser was successfully implemented by the example of a chemical laser.

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