Quantum Electronics **32** (2) 183 – 184 (2002)

PACS numbers: 42.55.Lt; 42.60.Lh
DOI: 10.1070/QE2002v032n02ABEH002154

Once again on the efficiency of a nitrogen laser

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***Abstract*. Attention is drawn to the problem of increasing the efficiency of a nitrogen laser. The possibility of creating efficient UV and VUV sources using nitrogen and hydrogen lasers is discussed.**

Keywords: *efficiency of a nitrogen laser, pump power in plasma-voltage maximum, runaway electron beam.*

In a paper concerning the efficiency of a nitrogen laser published in the June 2001 issue of Quantum Electronics, V.F.Tarasenko [1] made a number of critical remarks about our paper [2]. We consider it is our duty to give an exhaustive reply to these remarks since they concern the basic physical and technical aspects of the problem under study.

In our paper [2], the dependences of the maximum voltage $U_{\rm m}$ across a discharge gap, the parameter $E_{\rm m}/p = U_{\rm m}/(pd)$ (where d is the separation between electrodes), the output radiation energy W, and the efficiency η of a nitrogen laser are presented as functions of the basic parameters of the pumping scheme such as the nitrogen pressure p, the peak pump power $P_{\rm m}$, and the parameter ZC (where Z and C are the equivalent wave impedance and the capacitance of the pumping oscillator, respectively). These dependences are based on the experimental data obtained from the current and voltage oscillograms. It has been stated in Ref. [1] that we made errors in the measurements of $U_{\rm m}$. As a matter of fact, we have been carrying out such measurements for over 20 years. To prove that our data were incorrect, the author of Ref. [1] had to present analogous dependences based on the results of 'correct' measurements, since his statement would become meaningless otherwise.

The results of calculations presented in [1] show that the efficiency of the nitrogen laser rather weakly depends on E_0/p (see Fig. 7 in Ref. [1], $E_{\rm m}[2] \equiv E_0$). For example, the theoretical value of the efficiency varies only by 6 % – 7 % in the interval of working values of $E_0/p = 150 - 200$ V cm^{-1} Torr^{-1} recommended in Ref. [1]. This is quite natural because the excitation efficiency of the upper laser levels decreases with decreasing E_0/p, but the discharge power and the energy input required for their excitation increase due to an increase in the plasma resistance. Therefore, the experimental fact established by us that the variation of the parameter $E_{\rm m}/p$ does not alter the nitrogen laser parameters significantly in the range of working pressures is quite valid and not erroneous as claimed in Ref. [1].

The author of Ref. [1] has considered the simplest pumping scheme and presented the calculated pulse shapes (Fig. 3) in which, unlike our work (see Fig. 2 in [2]), the voltage pulse front length is equal to zero. Naturally, the maximum voltage across the discharge gap in this case is always equal to the maximum voltage of the pumping oscillator, and the discharge is formed only after the voltage pulse maximum, since there exists a finite delay time of the breakdown which depends on E_0/p. However, such a situation is not realised in actual practice. We used in Ref. [2] the scheme with a recharging of the capacitances, in which the duration of the voltage-pulse front in the free-running mode is $t_{\rm f} \approx 100$ ns, and the amplitude is $U_0 \approx 40$ kV. In this case, the ionisation and pumping of the active medium were started at the voltage-pulse front. This means that, unlike [1], the discharge was triggered under our experimental conditions up to the maximum free-running voltage in the time interval $t = 0 - 100$ ns, and a linear dependence of $U_{\rm m}$ on p was observed, where $U_{\rm m} \leqslant U_0$.

In Ref. [2], we spoke about the peak pump power, which corresponds to the discharge voltage maximum, but is not the maximum power supplied to the discharge. The peak pump power first increases and then decreases with increasing p, attaining its maximum at the point $U_{\rm m} = U_0/2$ (matched discharge regime). The peak power and the electron temperature in the discharge attain simultaneously their maximum values just in the vicinity of this point, and the optimal conditions for the excitation of the nitrogen laser are also produced here. However, we have not mentioned anywhere in our work [2] that the maximum pump power is achieved for the maximum plasma voltage, as was claimed in Ref. [1]. The power at the discharge voltage peak, which was mentioned in Ref. [2], is erroneously identified in Ref. [1] with the maximum power that is attained near the current maximum, but at a lower electron temperature of the plasma than at the voltage maximum.

The nitrogen laser is pumped most efficiently under the conditions of the highest electron temperature existing for several nanoseconds in the discharge, so that the pump

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Received 11 October 2001
Kvantovaya Elektronika **32** (2) 183 – 184 (2002)
Translated by Ram Wadhwa

power is the main factor determining the energy input and the lasing efficiency under these conditions (see Fig. 6 in Ref. [2]). It is obvious from a comparison of the pumping schemes with one (Fig. 1 in [1]) and two discharge circuits (Fig. 1 in [2] for a saturated choke L_2) that the pump power at the voltage maximum for the scheme in Ref. [1] is equal to zero and the laser is pumped during the fall of the voltage pulse. However, in both cases the active medium will be most efficiently excited in the matched discharge regime at the instant of time when the voltage across the discharge gap is $U_{\mathrm{m}} = U_0/2$, because high values of E/p and of the pump power are realised simultaneously at this instant. In addition, the efficiency of the nitrogen laser in both cases should depend on the parameter ZC [2], this parameter being equal to $ZC = (LC)^{1/2}$ in Ref. [1]. The single circuit scheme is ideal and cannot be realised in practice because of the presence of the parasitic capacitance and the inductance of the discharge gap.

It was shown in Ref. [2] that the energy supplied near the voltage maximum plays an important role in the case of a two-circuit laser pumping. To enhance the efficiency of the nitrogen laser, the fraction of this energy should be increased by increasing the power which, in turn, is limited by the total inductance L_Σ of both discharge circuits [2]. Thus, the value of L_Σ should be minimised to improve the efficiency of the laser.

The author of Ref. [1] has analysed the relevant papers in the light of the data obtained by him long before the publication of our work [2]. We are aware of these publications, but they fail to provide a clear idea about the dependence of the nitrogen laser radiation parameters on the pumping system parameters, and about the large spread in the laser efficiency given in various publications, which is hard to explain. The main purpose of our work [2] was to obtain a clear answer to these and other important questions.

According to the author of Ref. [1], the limiting efficiency of a nitrogen laser is $\sim 0.3\,\%$, which obviously makes it less competitive than the ecologically hazardous excimer lasers. However, the interest to the problem of increasing the efficiency of nitrogen lasers remains undiminished. On the other hand, the unique potentialities of the nitrogen laser, e.g., a high quantum efficiency ($\sim 19\,\%$), the absence of degradation, and the nontoxic working medium, as well as the simplicity of its construction, have made it an object of persistent attention. The problem of building a reliable and highly efficient nitrogen laser is also stimulated by the rapid development of semiconductor lasers which are considerably superior in compactness, reliability, and ecological requirements to the known UV gas lasers, but are quite expensive at present.

The analytic paper [1] does not mention any works suggesting new ways of solving this problem. For example, it was reported in Ref. [3] that a 20-J laser with the efficiency 0.48 % was fabricated by using magnetic compression of the pump pulse to provide a nanosecond duration of its front, and by applying an angle cathode. We proposed in [4–6] the use of a beam of runaway electrons in the discharge to increase the fraction of 15 ± 2-eV electrons that excite the upper laser level $\mathrm{C}^3\Pi_u$ most effectively. The ~ 10-keV runaway electrons were produced in the cathode layer of an abnormal discharge, and then were injected into the discharge gap with an external electric field that maintained the balance between the energies gained and lost by these electrons over the entire discharge gap. Under such conditions, the runaway electrons are capable of propagating over infinite distances, efficiently ionising and exciting the gas.

The method proposed by us in [4–6] makes it possible to obtain powerful beams of runaway electrons for large values of *pd* corresponding to the right branch of the Paschen curve. In view of the above, the application of this method in high-power gas lasers seems to be quite promising, especially in the UV and VUV lasers with high-frequency electron transitions.

The rapid progress in photolithography in recent years, as well as the use of laser technologies in medicine and various branches of industry, etc., requires the creation of short-wavelength lasers emitting in the VUV spectral range [6]. The main attention in this case is paid to a 157-nm F_2 laser [7, 8], despite the fact that it has all the drawbacks of excimer lasers, which are aggravated by a very high pressure of the active medium (more than 10 atm). A 160-nm H_2 laser may serve as an alternative to the F_2 laser. The mechanisms of population inversion in hydrogen and nitrogen molecules are identical as a whole, so that the H_2 laser also has a very low technical efficiency in some known experimental realisations. In this connection, the problems of creating highly efficient nitrogen and hydrogen lasers based on runaway electrons are closely related. These problems are of considerable scientific interest, they are important from the point of view of technical applications and are the subject of lively discussions in the scientific literature [2–6, 9].

Thus, the paper by V.F.Tarasenko [1] does not truly reflect the trends in the nitrogen laser development. It contains obsolete scientific material, and the critical remarks made in it about our work are unsubstantiated.

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