Effects of Simmer Current on Flashlamp Impedance and Their Combined Influence on the Output of a Quasi-CW Nd:YAG Laser

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***Abstract*—This paper reports the results of investigations carried out on the influence of simmer current on flashlamp impedance and performance of a flashlamp-pumped Nd:YAG laser operating in the quasi-CW mode. A pulse power source with an adjustable output pulsewidth (1–20 ms) and an adjustable simmer current source (30 mA to 6 A) developed specifically for the study were used. It is found that the simmering of the lamp reduces the impedance factor of the lamp, increases the correct arc diameter, and reduces the peak current density of the flashlamp discharge. It improves the efficiency of the flashlamp pump source and, hence, the efficiency of the Nd:YAG laser also. An appropriate choice of the simmer current, using the results obtained, can lead to higher efficiency of the laser and increased life of the lamp.**

***Index Terms*—Flashlamp impedance, Nd:YAG laser, quasi-CW laser, simmer current, solid-state lasers.**

I. Introduction

PULSED operation of lasers is quite useful for several material processing applications [1]. The quasi-CW operation of neodymium lasers make them desirable for various material processing applications such as hole piercing, deep key hole welding, and cutting [1]–[3]. It was found quite early that the lifetime of the lamp could be significantly increased if the gas in the lamp was preionized [4]. Flashlamp-pumped solid-state lasers, therefore, use the simmer mode of operation in which flashlamps are kept ionized by a low current discharge maintained between the high current pulses. Typical values of the dc simmer current lie between 25 mA to several amperes [5]. Preionization provides the additional advantage of improving the flashlamp efficiency [6], [7] and is therefore widely used for these solid-state lasers. Gains in efficiency as high as 100%, as a result of preionization, are reported for short-pulsed flashlamps used in dye lasers [8]–[10]. For the majority of quasi-CW solid-state lasers, flashlamps are driven by a pulsed current having a duration in the range of 1–20 ms; the gain in efficiency is not of this level.

In this paper, investigations of the influence of dc simmer current on the output of a Nd:YAG laser operating in the quasi-CW mode with an output pulsewidth in the range of 1–10 ms are reported. This laser is capable of giving high average power (hundreds of watts) and can operate at high repetition rates (typically 100–500 Hz). In the experiment described here, the lasing medium was pumped by using a pulse power source with a provision of the fine adjustment in current pulse parameters, i.e., pulsewidth, pulsed-current magnitude, and pulse repetition rate over a wide range.

The experimental results presented show that the flashlamp impedance and correct arc diameter depend on the value of the dc simmer current and, therefore, the peak current is varied by the changes in the simmer current. The conversion efficiency also improves with the simmer current as the pump source efficiency improves with an increase in the correct arc diameter.

II. Theory

The Goncz relation, describing the relation between the flashlamp voltage and the flashlamp current during a discharge pulse, states that the voltage is always proportional to the square root of the current in the high-current regime [4]:

$$V_o = K_o\sqrt{I_o}. \tag{1}$$

The flashlamp impedance parameter K_o depends on the geometric dimensions of the flashlamp, such as the arc length l and the bore diameter d of the lamp, and on the lamp filling (e.g., the kind of gas and the pressure p). For xenon, the following relation holds where pressure p is in torr [4]:

$$K_o = 1.27(p/450)^{0.2} l/d. \tag{2a}$$

In (2a), the whole cross section of the flashlamp is assumed to be ionized. Because the instantaneous arc diameter is not identical to the geometric inner diameter of the lamp, (2a) has to be modified. The bore diameter is replaced by the correct arc diameter d_a as proposed by Dishington *et al.* [11]

$$K_o = 1.27(p/450)^{0.2} l/d_a. \tag{2b}$$

Therefore, for a fixed value of pressure p and arc length l, the flashlamp impedance is no longer a constant but depends on d_a. The dependence of flashlamp impedance parameter on d_a can, in turn, be used to define the correct arc diameter d_a:

$$d_a = 1.27(p/450)^{0.2} l/K_o. \tag{2c}$$

The dynamic behavior in the discharge circuit, which consists of a flashlamp, a capacitance, and an inductance, is described by

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a nonlinear differential equation that contains the Goncz relation. To classify the numerical solutions of the flashlamp current while neglecting any Ohm's resistance, Marciewicz and Emmett [12] introduced the parameter α. By computer simulation, the most accurate value for α_o (α for the critically damped case) was calculated to be 0.84 by Brown and Nee [13], whereas smaller values have been reported before [12], [14].

In the present experiment, the flashlamp was driven by rectangular pulsed currents in place of pulses generated by critically damped *RLC* discharge circuits used for narrower pulses or by multiple-mesh pulse forming networks. A buck converter operating at high frequency and in the burst mode was used, the details of which are reported elsewhere [15], to generate the rectangular pulses with provisions for pulse parameter adjustment. It facilitates the fine adjustment in pulsewidth, current, and repetition rate over a wide range. The output voltage of the converter-based pulse power source depends on input voltage V_{in} and the duty ratio D of the switch as given by [16]

$$V_o = DV_{\text{in}}. \tag{3}$$

The current I_o through the flashlamp can also be controlled by the duty ratio through the control function, as given by

$$I_o = K_v D^2 \tag{4}$$

will not be linear (where $K_v = (V_{\text{in}}/K_o)^2$).

The parameter K_v, which depends on input voltage V_{in} and flashlamp impedance parameter K_o, can be treated as constant for a constant input voltage and for the lamp operating in the high-current regime.

The reflection of the ripple current, through the flashlamp, in the laser output can be minimized by choosing a high switching frequency f_s (30 kHz in the present experiment). In addition, the output voltage fluctuations ΔV_o given by

$$\Delta V_o/V_o = 0.5\pi^2(1-D)(f_c/f_s)^2 \tag{5}$$

are very much reduced by using a low-pass filter with appropriate corner frequency f_c [16]

This will result in a peak-to-peak current ripple ΔI_o given by

$$\Delta I_o/I_o = \pi^2(1-D)(f_c/f_s)^2 \tag{6}$$

through the flashlamp having a *V–I* characteristic in the region of interest as per (1).

By choosing appropriate values of switching and corner frequency, the peak-to-peak ripple current can be contained so as to result in a negligibly small contribution in laser output. Using a converter-based pulse power source, the laser could be pumped by rectangular pulsed currents, through the flashlamp with desirable pulse parameters, in the pulse duration range of 1–20 ms to study the effect of the simmer current on laser output operating in the quasi-CW mode.

III. Experimental Setup

A simplified schematic diagram of the experimental arrangement used for the study is shown in Fig. 1. It consists of the following subsystems.

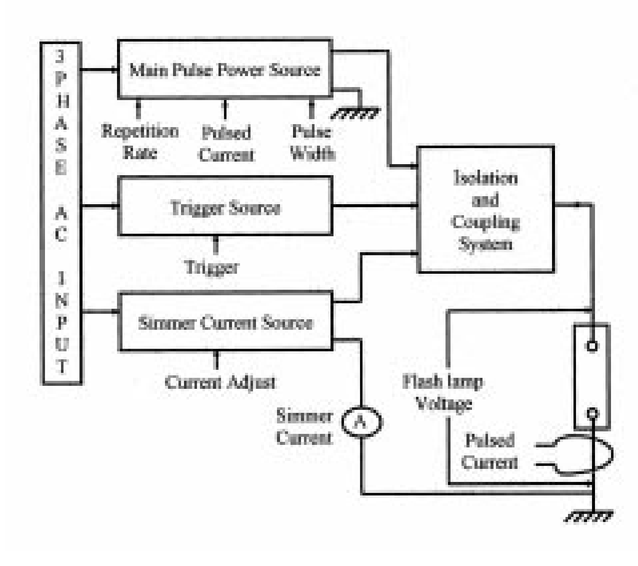

Fig. 1. Schematic diagram of the experimental arrangement for measurement of flash lamp pulsed-current and voltage.

A. The Pulsed Power Source

A pulsed power source, with adjustable output current-pulse parameters, specifically developed for this purpose was used. It can deliver an average output power of 2 kW and a peak output power of 50 kW to drive the flashlamp-pumped quasi-CW Nd:YAG laser oscillator to get an average power output up to 20–40 W. It uses a series type of chopper to facilitate fine adjustment in pulse parameters (i.e., pulsewidth, current, and repetition rate) over a wide range. The output current is continuously adjustable from 50 to 200 A, the pulsewidth from 1 to 20 ms, and the repetition rate from 1 to 500 pulses per second.

B. The Simmer Current Source

For studying the effects of simmer current on flashlamp impedance and laser output, a simmer current source which can deliver an adjustable stable current from 30 mA to 6 A through the flashlamp has been developed along with a trigger system using a parallel trigger technique. Different values of ballast resistors are used to get different ranges of stable simmer current. To keep the power dissipation in ballast resistors within reasonable limits even for higher values of simmer current, different dc power sources, with suitable maximum voltage and power capabilities, are used with these ballast resistors. These power sources are kept active individually or in combination, depending upon the current requirements.

At the time of triggering, the simmer current source is operated at 100 mA of current and is then adjusted as per the requirements. This requires only a 45-kV 200-mA diode stack to be used for isolating the simmer current source from the trigger source high-voltage pulses, even for a simmer current requirement of 6 A. The high-voltage low-current source is kept active in parallel with the high current source to avoid extinction of the simmer, due to lower output voltage from the high current source, just after the main pulsed discharge.

C. The Laser System

The experiments were carried out using an optical pumping chamber with separate axial holes for the laser rod and for the flashlamp as well as a water circulation arrangement for cooling them. The pump cavity from inside was a highly reflective elliptical cylinder with the laser rod and flashlamp pump at each focal line. The flashlamp had an impedance parameter of 16.2 V/$\sqrt{A}$, an arc length of 76.2 mm, and a bore diameter of 5 mm. The laser rod was 8 mm in diameter and 85 mm long, with perpendicular flat ends without an antireflective coating. The optical resonator had a length of 40 cm and consisted of a high reflector with a 5-m radius of curvature and a flat output coupler with a transmission of 50%.

D. The Cooling System

The efficiency of a quasi-CW Nd:YAG laser is typically 1%–2%. Therefore, almost 98%–99% of the input energy appears as heat which has to be extracted from the optical pump cavity by an appropriate cooling system. The laser rod and flashlamp are cooled separately and the temperature of the pumping cavity is maintained between 14 °C–20 °C. The cooling system uses distilled and deionized water as the coolant.

E. The Measurements and Instruments

The flashlamp was driven by the pulsed power source in the presence of a simmer current discharge for carrying out the experimental study. The data for the flashlamp current, voltage, and laser output energy per pulse were recorded under operation at a repetition rate of one pulse per second to avoid the influence of repetition rate on flashlamp impedance and, thus, ensuring that the effects on flashlamp parameters are due to simmer current only. These data were averaged for 10 consecutive pulses to account for pulse-to-pulse variations. The signals were recorded using a digital storage oscilloscope, LeCroy model 9314A, with a bandwidth of 400 MHz and a sampling rate of 100 MS/s from which the data were transferred to a PC for storage and further analysis. To ensure correct measurements of the pulsed current through the flashlamp, a pulse transformer designed and fabricated for this purpose was calibrated using a shunt that had a resistance of 5 mΩ with an accuracy of 1%. An oscilloscope probe with an attenuation ratio of 100:1 and a bandwidth of 200 MHz was used to measure the voltage across the flashlamp. The laser energy was measured by using a Gentec model ED200 energy meter along with the above-mentioned scope. The calibration of the energy meter was confirmed experimentally with another recently calibrated energy meter (Gentec model ED200). The energy meter output was also averaged for the same 10 consecutive pulses, for which current and voltage pulses were averaged, and stored.

IV. Experimental Study

The power conditioning system for the flashlamp-pumped solid-state laser was connected to feed the flashlamp in the pumping chamber. To begin with, the cooling system was activated and then the input contactor was energized to feed the power to the power-conditioning system for the laser. The simmer current source was then applied and the flashlamp was triggered under applied bias voltage from the current source. The triggering causes the simmer current to flow through the flashlamp, which is adjusted to get the required value of 100 mA. The main pulse power source isolation switch, incorporated in the isolation and coupling system, is switched on to feed the pulsed power after sensing the water flow, the temperature of coolant water flowing through the pumping chamber, and the appropriate simmer current magnitude. For these experiments, the pulsewidth of the flashlamp current pulse is adjusted for 100 mA of the simmer current as the pulsewidth varies slightly with a change in simmer current value.

To determine the dependence of the laser output on the simmer current, the averaged waveform of the voltage across the flashlamp, the current through it as a function of time, and the laser output energy per pulse were recorded simultaneously at selected values of the pulsewidth for simmer currents varying from 30 mA to 5 A in a large number of steps. The experiment was carried out at a minimum adjustable pulsewidth of 0.85 ms and at other pulsewidths of 1.35, 1.85, and 2.85 ms. The electrical pump energy and conversion efficiency were calculated from these experimentally measured parameters. The electrical pump energy is the electrical energy per pulse delivered to the flashlamp. The conversion efficiency is the ratio of the laser output energy per pulse and the corresponding electrical pump energy. The values of conversion efficiency under various settings of simmer current at these current pulsewidths are summarized in Table I.

TABLE I
CONVERSION EFFICIENCY AS A FUNCTION OF SIMMER CURRENT FOR FLASHLAMP CURRENT PULSEWIDTH VALUES OF0.85, 1.35, 1.85 AND 2.85 ms

Simmer current (mA)	Conversion efficiency (%) @ Current pulse width			
	0.85 ms	1.35 ms	1.85 ms	2.85 ms
30	1.07	1.42	1.61	1.70
40	1.23	1.55	1.68	1.70
50	1.37	1.61	1.73	1.73
60	1.48	1.70	1.75	1.78
70	1.79	1.66	1.73	1.77
80	1.79	1.69	1.80	1.78
90	1.82	1.75	1.79	1.79
100	1.79	1.70	1.77	1.79
200	1.93	1.88	1.84	1.83
300	1.87	1.90	1.86	1.82
400	1.92	1.97	1.87	1.83
500	1.97	1.97	1.88	1.84
1000	2.01	1.92	1.87	1.82
1500	2.07	1.94	1.87	1.81
2000	2.08	1.92	1.85	1.84
2500	2.13	1.93	1.83	1.84
3000	2.13	1.94	1.85	1.84
3500	2.10	1.98	1.82	1.84
4000	2.10	1.99	1.86	1.83
4500	2.14	1.97	1.85	1.83
5000	2.13	2.00	1.85	1.81

The conversion efficiency, for a pulsewidth of 0.85 ms, improves from about 1% at 30 mA to about 2% at 1 A of simmer current; beyond this value, the improvement in efficiency is negligibly small. For current pulsewidth values of 1.35, 1.85, and 2.85 ms, the improvement in efficiency is observed up to 400, 300, and 200 mA, respectively, and beyond these values of simmer current no appreciable improvement is observed. It is noted from these results that the efficiency improves with increasing simmer current value considerably up to 500 mA but does not improve further, which was experimentally verified up to 5 A.

For an investigation of the gain in pump efficiency, which is not totally understood, the flashlamp impedance is examined as a function of the simmer current, from which the correct arc diameter [11], [17] is calculated. The observation of the correct arc diameter allows one to describe the effect of the simmer current on the flashlamp discharge.

From the measured parameters at pulsewidth values of 0.85, 1.35, 1.85 and 2.85 ms and at large number of simmer current values in the range from 30 mA to 5 A, the flashlamp impedance parameter and flashlamp correct arc diameter were calculated. The flashlamp impedance parameter K_0 was determined according to the Goncz relation, as given in (1), from the corresponding measured values of voltage and current during the whole discharge. The value of correct arc diameter was calculated from measured flashlamp impedance according to (2c).

The flashlamp impedance parameter K_0 was found to decrease with an increase in the simmer current. The impedance offered by the flashlamp was higher for narrower pulses at the same value of simmer current in the lower range and approached a final value at higher levels of simmer current. The total percentage change decreased with increasing pulsewidth, and flashlamp impedance approached the final value at lower values of simmer current for wider pulses.

It is also observed that the correct arc diameter increased with rising simmer current and approached the geometric bore diameter of the lamp tube at higher values of simmer current. The total percentage change in correct arc diameter decreased with increasing pulsewidth and it approached the geometric bore diameter, for wider pulses, at lower values of simmer current. It approached the geometric bore diameter of the tube between 600 mA and 1 A for 0.85 ms, at 500 mA for 1 ms, between 400 and 500 mA for 1.35 ms, and between 100 to 200 mA for 2.85 ms.

For the study of the relative effect of simmer current on laser output with different values of pulsewidth, flashlamp pulsed current, voltage, and output laser energy per pulse were recorded at pulsewidths from 1 to 10 ms at an interval of 1 ms with the same setting and alignment of the laser system and other instruments. The temporal evolution of the pulsed current and voltage across the flashlamp observed as a function of the simmer current but for identical input is shown in Fig. 2. As the conversion efficiency improved up to a simmer current of 500 mA for the current pulsewidths varying from 0.85 to 2.85 ms, further measurements for current pulsewidths 1–10 ms were carried out only at five selected simmer current values of 30, 50, 100, 200, and 500 mA. Flashlamp pulsed-current density was kept approximately at 1000 A/cm^2 for this set of experiments.

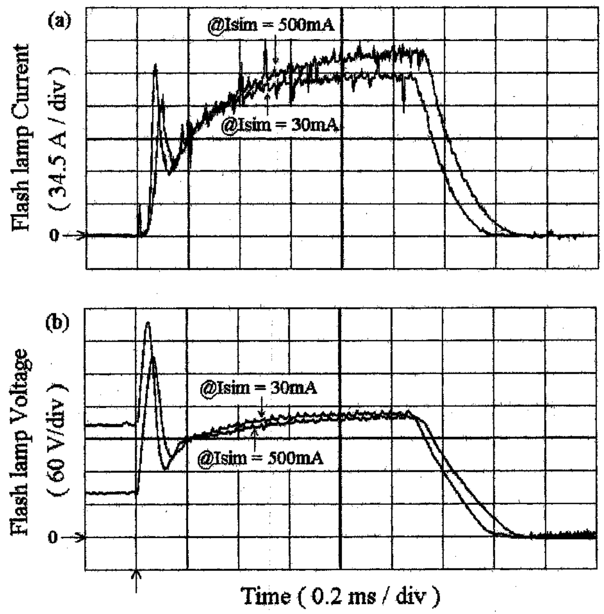

Fig. 2. Flashlamp (a) pulsed-current and (b) pulsed-voltage waveforms for two different values of simmer current. The signals were averages over 10 pulses.

The electrical pump energy per pulse delivered to the flashlamp was increased from 40 to 400 J in steps of 40 J with a peak power dissipation of 40 kW and corresponding laser output energy per pulse varied from 0.5 to 7.5 J. The pulsed current, voltage, and laser energy per pulse measured at these values of pulsewidth and simmer current are tabulated in Tables II–IV, respectively. The electrical pump energy and conversion efficiency were calculated from the measured parameters for each setting of pulsewidth and simmer current values. The conversion efficiency values at these different settings are summarized in Table V and are also plotted in Fig. 3. Corresponding flashlamp impedance and correct arc diameter were calculated, from the recorded parameters at different pulsewidth values from 1 to 10 ms, and are plotted as functions of simmer current in Figs. 4 and 5, respectively.

V. Results and Discussion

The laser output energy was observed as a function of the simmer current for different values of pulsewidth from 1 to 10 ms. The conversion efficiency increased with increasing simmer current. As the only change, which caused this improvement in conversion efficiency of the laser system, is a change in the simmer current, it can be concluded that the pump source efficiency improves with this change in simmer current. The experimental results obtained for conversion efficiency at different pulsewidths from 1 to 10 ms are plotted as a function of simmer current in Fig. 3. Clearly, the strongest change in the efficiency occurs when the simmer current is increased from 30 to 500 mA. For simmer currents greater than 500 mA, the laser efficiency reaches nearly a constant value. The 100% improvement in efficiency [i.e., from 1% to 2% due to simmer current at a pulsewidth of 0.85 ms (see Table I)] is significantly larger than the relative uncertainties. The effect, due to an increase in simmer current, is reduced as the pulsewidth became wider.

TABLE II
FLASHLAMP PULSED CURRENT AS A FUNCTION OF SIMMER CURRENT FOR DIFFERENT VALUES OF PULSEWIDTH FROM 1 TO 10 ms

Pulse width (ms)	Flash lamp pulsed-current (A) @ Isim = 30 mA	@ Isim = 50 mA	@ Isim = 100 mA	@ Isim = 200 mA	@ Isim = 500 mA
1.0	164.4	171.6	182.5	184.8	185.1
1.5	168.0	177.6	184.1	184.9	184.6
2.0	168.3	177.6	181.0	183.5	184.1
3.0	171.1	179.4	183.2	186.1	189.4
4.0	179.1	184.3	187.8	190.1	200.0
5.0	179.5	180.1	182.4	186.5	191.1
6.0	173.4	179.2	180.1	184.4	186.7
7.0	175.2	176.0	178.9	182.3	186.6
8.0	175.3	175.2	183.0	185.2	190.1
9.0	174.6	180.5	181.7	185.6	188.6
10	173.9	177.6	184.3	186.5	189.3

TABLE III
FLASHLAMP PULSED VOLTAGE AS A FUNCTION OF SIMMER CURRENT FOR DIFFERENT VALUES OF CURRENT PULSEWIDTH FROM 1 TO 10 ms

Pulse width (ms)	Flash lamp pulsed-voltage (V) @ Isim= 30 mA	@ Isim = 50 mA	@ Isim = 100 mA	@ Isim = 200 mA	@ Isim = 500 mA
1	230.2	227.7	224.8	222.9	221.0
1.5	232.2	227.8	224.5	222.5	222.2
2	230.7	225.2	223.2	221.2	220.7
3	226.5	222.3	222.8	221.7	220.3
4	225.7	223.7	224.2	223.8	222.5
5	222.7	218.5	217.8	216.6	215.3
6	217.0	213.8	213.3	211.8	210.2
7	215.0	212.2	209.3	209.3	209.3
8	212.5	206.3	210.3	209.9	209.5
9	208.7	208.2	207.2	207.2	206.7
10	206.2	207.3	207.8	207.4	207.0

The percentage increase in efficiency decreased from about 27% to only about 1%, when the pulsewidth was increased from 1 to 7 ms for simmer current varying from 30 to 100 mA. The percentage increase in conversion efficiency for pulsewidth values of 2, 3, and 5 ms, for the identical change in simmer current, is observed to be 15%, 7%, and 5% respectively.

The experimental results obtained for flashlamp impedance are plotted as a function of simmer current for different values of current pulsewidth in Fig. 4. The impedance factor K_0 decreased with increasing simmer current. Although at lower simmer currents the flashlamp impedance decreased faster with increasing simmer current, it reaches a nearly constant value at a simmer current of about 500 mA. The flashlamp current and voltage waveforms for different values of simmer current (see Fig. 2) show an increase in peak current and a decrease in voltage across the flashlamp with increasing simmer current. A change in flashlamp impedance of about 13% and about 11% at pulsewidths of 0.85 and 1 ms, respectively, are significantly higher than the uncertainties in the experimental measurements, which are not more than 4%. The change in flashlamp impedance decreased with increase in pulsewidth as can be seen from Fig. 4. The percentage change in flashlamp impedance decreased from 11% at 1 ms to only 3% at 5 ms.

TABLE IV
LASER OUTPUT ENERGY PER PULSE AS A FUNCTION OF SIMMER CURRENT FOR DIFFERENT VALUES OF CURRENT PULSEWIDTH FROM 1 TO 10 ms

Pulse width (ms)	Laser output energy per pulse (J) @ Isim = 30 mA	@ Isim = 50 mA	@ Isim = 100 mA	@ Isim = 200 mA	@ Isim = 500 mA
1	0.498	0.580	0.690	0.755	0.765
1.5	0.964	1.084	1.203	1.222	1.277
2	1.373	1.551	1.648	1.701	1.738
3	2.138	2.309	2.405	2.445	2.494
4	2.956	3.081	3.333	3.387	3.556
5	3.816	3.986	3.994	4.141	4.223
6	4.328	4.410	4.669	4.663	4.632
7	5.144	5.173	5.173	5.312	5.530
8	5.738	5.715	6.094	6.251	6.555
9	6.532	6.681	6.726	6.898	7.023
10	7.014	7.119	7.311	7.504	7.594

TABLE V
CONVERSION EFFICIENCY AS A FUNCTION OF SIMMER CURRENT FOR DIFFERENT VALUES OF CURRENT PULSEWIDTH FROM 1 TO 10 ms

Pulse width (ms)	Conversion efficiency (%) @ Isim = 30 mA	@ Isim = 50 mA	@ Isim = 100 mA	@ Isim = 200 mA	@ Isim = 500 mA
1	1.343	1.515	1.716	1.834	1.909
1.5	1.631	1.769	1.921	1.980	2.052
2	1.768	1.939	2.039	2.095	2.138
3	1.838	1.930	1.964	1.975	1.992
4	1.828	1.869	1.979	1.990	1.998
5	1.930	2.048	2.033	2.050	2.075
6	1.907	1.909	2.015	1.990	1.958
7	1.940	1.968	1.963	1.989	2.012
8	1.930	1.982	1.984	2.010	2.062
9	1.985	1.969	1.978	1.991	1.995
10	1.956	1.934	1.909	1.940	1.938

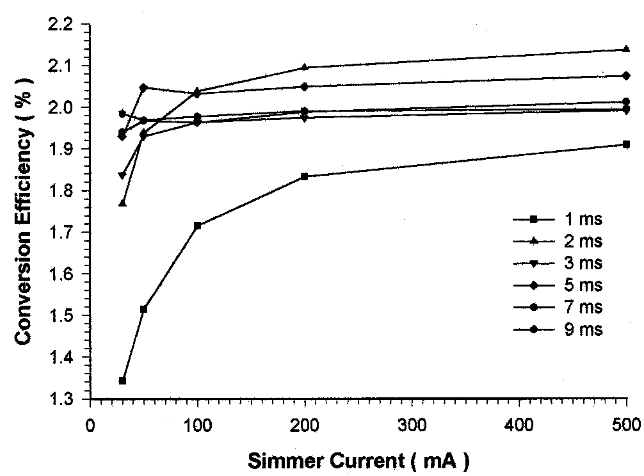

Fig. 3. Conversion efficiency plotted as a function of simmer current for different values of current pulsewidth.

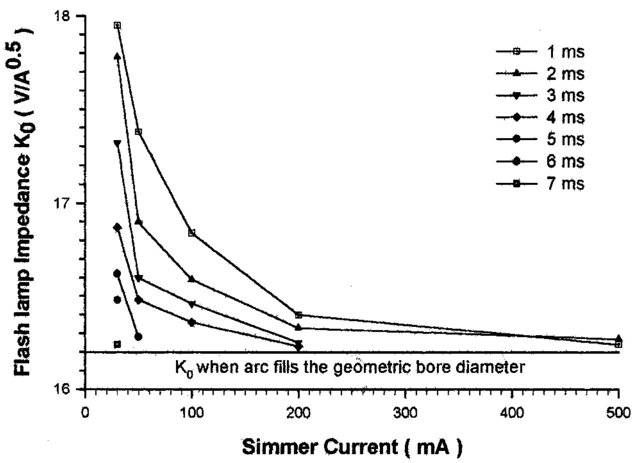

Fig. 4. Dependence of the flashlamp impedance on the simmer current for different values of current pulsewidth.

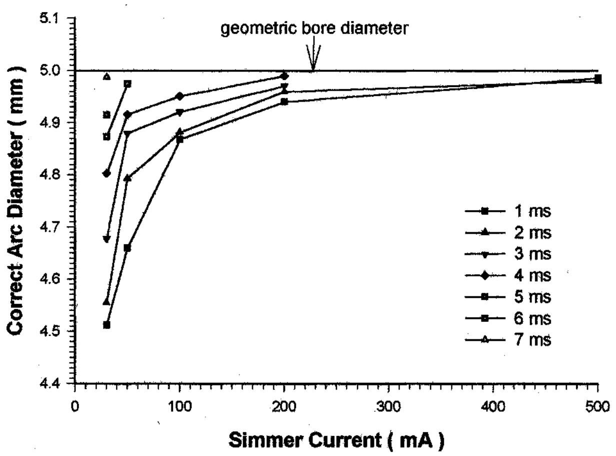

Fig. 5. Dependence of the correct arc diameter on the simmer current for different values of current pulsewidth.

The change for other pulsewidth values of 2, 3, and 4 ms is observed to be 10%, 7%, and 4%, respectively.

The results for correct arc diameter at different pulsewidth values from 1 to 10 ms are plotted as a function of the simmer current in Fig. 5. The correct arc diameter d_a increased with simmer current. Even though the total increase is small (10% relative to the bore diameter), it is higher than the relative uncertainties and, hence, it can be concluded that d_a is being influenced by the simmer current. When the simmer current exceeds 500 mA, the correct arc diameter approached a constant value even for a pulsewidth of 1 ms, which was found to be the same as the geometric bore diameter of the flashlamp. As a consequence, the peak current of the flashlamp was found to increase with the simmer current. The percentage change in arc diameter decreased with an increase in current pulsewidth. The change relative to the geometric bore diameter decreased from about 10% at 1 ms to about 3% only at 5 ms. At pulsewidths of 2, 3, and 4 ms, the percentage change is observed to be 9%, 6%, and 4%, respectively.

It can be observed that, for pulsewidths greater than 4 ms, the correct arc diameter fills the geometric bore diameter of 100 mA of the simmer current. It can also be observed that the efficiency of the laser system improves up to 100 mA of simmer current at a pulsewidth value of more than 4 ms, and no further improvement in efficiency is observed at a pulsewidth of 5 ms for higher simmer current. The correct arc diameter approaches the bore diameter between 600 mA to 1 A at a pulsewidth of 0.85 ms, and it can clearly be observed that the efficiency also attains nearly a constant value for simmer currents higher than 1 A. A similar trend can be observed, for all other values of the pulsewidth from 1 to 10 ms, that the efficiency also approaches nearly a constant value when the arc completely fills the geometric bore diameter of the flashlamp. The fact that the flashlamp efficiency is improved as a consequence of the increase of the correct arc diameter is in agreement with experimental results obtained for the lamp intensity [18].

The increase in correct arc diameter with an increase in simmer current causes the flashlamp current density to decrease. The best spectral overlap of the neodymium absorption bands with the spectrum of a xenon-filled flashlamp occurs at a color temperature of 4500–4700 K, which occurs at a low current density compared to those at which lamps are operated. At higher current densities, the lamp spectrum shifts to shorter wavelengths and the line emission becomes less prominent [19]. This also explains why the conversion efficiency is improved with an increase in simmer current in the region in which the correct arc diameter increases with the simmer current. The work done by earlier researchers [19], [20] also tends to indicate that the xenon flashlamp pumping efficiency for neodymium lasers monotonically increases with decreasing current density.

Also, the flashlamp light, which is not absorbed in the rod on the first pass, will be rereflected to the flashlamp as an elliptical cylinder imaging pump cavity was used. As the lamp current density is reduced, the optical opacity of the flashlamp arc is also reduced [21]. The cavity transfer efficiency decreases rapidly up to a current density of 1000 A/cm^2 with an increase in xenon flashlamp current density due to an increase in lamp arc opacity [20]. This effect can enhance the flashlamp pumping efficiency, especially for long pulses where the current density is low, for an imaging pump cavity.

The presence of these two mechanisms may be a part of the explanation of variation in maximum efficiency, shown in Fig. 3, with an increase in pulsewidth. Higher experimental precision may also be helpful in better understanding the effect of simmer current in the region of maximum efficiency.

With a proper choice of the simmer current value, the discharge becomes more homogeneous, which is characterized by the fact that the correct arc diameter fills the bore of the flashlamp and the correct peak current density decreases although the measured current increases. In this sense, a smaller correct peak current density may be seen as an indicator of a longer lifetime for flashlamps.

VI. Conclusions

The influence of the simmer current on the laser output, flashlamp impedance, and correct arc diameter were studied for varying widths of current pulse through the flashlamp.

The efficiency of the system was found to increase with simmer current up to a certain value and then remained nearly constant for further increases in simmer current. An optimized value of the simmer current can be determined for the system to get a better efficiency.

In addition, the flashlamp impedance was also studied along with correct arc diameter. It was found that the flashlamp impedance decreases and the correct arc diameter increases with increasing simmer current, which in turn provides a higher pump efficiency and also longer life of the flashlamps. The improvement in pump efficiency could be correlated with the increase in correct arc diameter. Therefore, an optimized value of the simmer current can be determined for the system to get not only better efficiency but also an improved flashlamp life.

The effect of simmer current on the output of the laser, flashlamp impedance and correct arc diameter was observed to reduce with increase in pulsewidth value and was quite negligible, for the present system, for pulsewidths wider than 5 ms and simmer current values higher than 500 mA.

With appropriate choice of the simmer current value, the correct arc diameter fills the whole cross section of the flashlamp. As a consequence, the pump source efficiency and the laser output of a Nd:YAG laser are increased. At the same time, the lifetime of the flashlamp may be prolonged.

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