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Study of the charging circuit of a pulsed solid-state laser power supply: A new concept of high charging efficiency and realization

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ABSTRACT

Based on physical theory, a new concept for achieving high efficiency in a solid-state laser power supply charging circuit is first introduced in this paper that is, from the fact that when an electron from a power source enters the energy storage capacitor, a potential drop would occur in this process. This *potential drop* is the essence of the energy loss in a charging circuit. If the *potential drop* is small, or even negligible, power supply with a higher efficiency can be achieved. According to this design theory, a highly efficient charging circuit can be obtained if a power source with a single continuous increased voltage slightly higher than that of the energy storage capacitor is employed. With the use of this proposed technique, a prototype of a pulsed YAG laser power supply with high charging efficiency and high voltage charging precision is implemented. The design idea and the experimental results are described and discussed in detail.

1. Introduction

Pulsed solid-state lasers have been used in many fields due to their unique advantages [1]: compact, stable and reliable, easy operation and maintenance, especially suitable for on-field apparatus applications, in lidar, laser-induced fluorescence and laser-induced breakdown spectroscopy for atmosphere, water and soil pollution monitoring [2–4].

The laser power supply is crucial and can affect all specifications of the laser beam. The key point for the design of laser power supply is the charging circuit for an energy storage capacitor, to which considerable efforts have been dedicated [5–7].

In a review of the development history of a charging circuit, several schemes such as an R–C charging circuit, an L–C resonant double-voltage converter charging circuit, a constant current charging circuit, a reactor current-limiting charging circuit, a step charging circuit and a pulse transformer charging circuit have been studied extensively in pulsed solid-state laser power supply over the past several decades. Compact, stable and reliable pulsed laser power supplies with a high charging efficiency and precision have been achieved with the development of high-power and high-speed electronic components. However, up to now most of the techniques employed for improving charging efficiency were through the use of complex electrotechnics. This makes the charging circuit much complex; thus, the charging efficiency is affected by many electronic components.

Voltage conversion was done with a transformer in conventional solid-state laser power supply, such as resonance and L–C constant-current charge power supply. The main shortages were ponderous and expensive. The voltage conversion method with a transformer, in which the typical charging circuit employed by most laser manufacturers is switching convert techniques with SCR, was abandoned in laser power supply from the 1970s. With the appearance of automatic high-speed switches including VMOS and IGBT, they have been used in high-power switching converter laser supply from the late 1980s; this was a large step forward towards high efficiency and high stability of a solid-state laser power supply. In the 1990s, with the rapid progress of power MOSFET technology, the development of solid-state laser power supply from a medium-frequency inverse to a high-frequency inverse, SCR was replaced by high-power MOSFET; it raised pulsed solid-state laser power supply to a brand new level. There has been almost no progress in the solid-state laser power supply technique in recent years; only a few research works about CO_2 laser power supply were reported [8–10].

In this research work we investigate the means for improving the charging efficiency from a physical standpoint, and a prototype based on this theory is shown.

2. Potential drop—the essence of energy loss

Many researchers have explored attainment of high charging efficiency from the viewpoint of mathematics or electrotechnics. In this research, we introduce a brief physical concept to achieve high efficiency in a charging circuit. The process of charging is

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only electron energy transfer from a charging power supply to a storage capacitor, and takes account of neither the impact loss of electron collisions and the resistance of the charging circuit, nor absorption and release by an inductor/capacitor. The new concept of high charging efficiency can be described as follows: when an electron from a power source enters the energy storage capacitor, a potential drop may occur in this process. This potential drop is the essence of the energy loss in a charging circuit. If the potential drop is small, a power supply with higher efficiency is achieved. According to this, a high-efficiency charging circuit can be achieved if we have a power source with a single continuous increasing voltage, and its voltage is slightly higher than the capacitor's energy storage with no need for voltage with a linear increase or a constant charging current.

Fig. 1 shows a brief charging circuit; U_P is the voltage of the power source, C_S is the storage capacitor and SCR is the charging thyristor switch.

If we assume that the storage capacitor (C_S) voltage is 0 before charging U_P, at the end of charging, it takes in a total of N electrons to fulfil the process. Therefore, the charge efficiency of each electron can be written as $(2N-1)/2N$, and the total charge efficiency as $N/(N+1)$. The results are shown in Fig. 2.

From Fig. 2 we can see that the charging efficiency is only 50% at the first electron charge into the storage capacitor, and it increases along with increasing electron numbers. If a storage capacitor of 100 μF is charged, about 10^{18} electrons are required. On increasing the charge electrons the efficiency will also increase. The lower charging efficiency from the onset contributes to the difference in the initialization voltage of the storage capacitor and power source. Therefore, we should decrease the voltage difference (ΔV) between the power source and the storage capacitor if a high charging efficiency is desired. Fig. 3 shows the efficiency curve at different ΔV with increasing power source voltage.

From Fig. 3 we can see that a high charging efficiency is achieved at lower ΔV; if we can avoid or reduce ΔV, a higher charging efficiency can be achieved. If there is no ΔV appearance we cannot charge in theory, it is therefore necessary to make ΔV as small as possible. This explains why the efficiency is 50% in an R–C circuit and why the efficiency will increase with subdividing voltage in a staircase voltage power supply. The high efficiency of resonant charging can be regarded as a potential drop occurring in the process of charging though inductor absorption and release of energy, and the constant-current charging and pulse transformer charging all lead to a circuit of potential drop to almost zero.

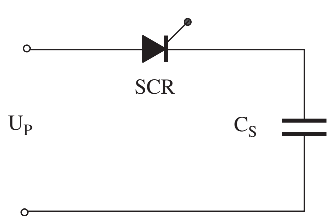

Fig. 1. A brief charging circuit.

3. Charging power source

From the concept described above, a power source with a single continuous increasing voltage slightly higher than that of the storage capacitor and a small ΔV is required. If we make one power supply system the charging power source, it will consume power energy and may be cumbersome and potentially a very large laser power supply. One simple means of achieving high efficiency is to use the alternating current (AC) from a power plant supply; it was 50 Hz, 220 or 380 V. Here we consider only a single-phase AC 220 V, and Fig. 4 shows the original voltage waveform of AC power from a power plant and after adding one heightening DC voltage. From the original voltage waveform we can see that the 0–A and B–C segments all have a single continuous increasing voltage, but for storage capacitor charging, it usually begins from 0 V. Thus, 0–A satisfies our needs, but its maximal value is only 311 V. If we add one DC voltage equal to the maximal value 311 or 537 V, we will obtain 622 and 1074 V for AC 380 V, and it will be useful for many applications.

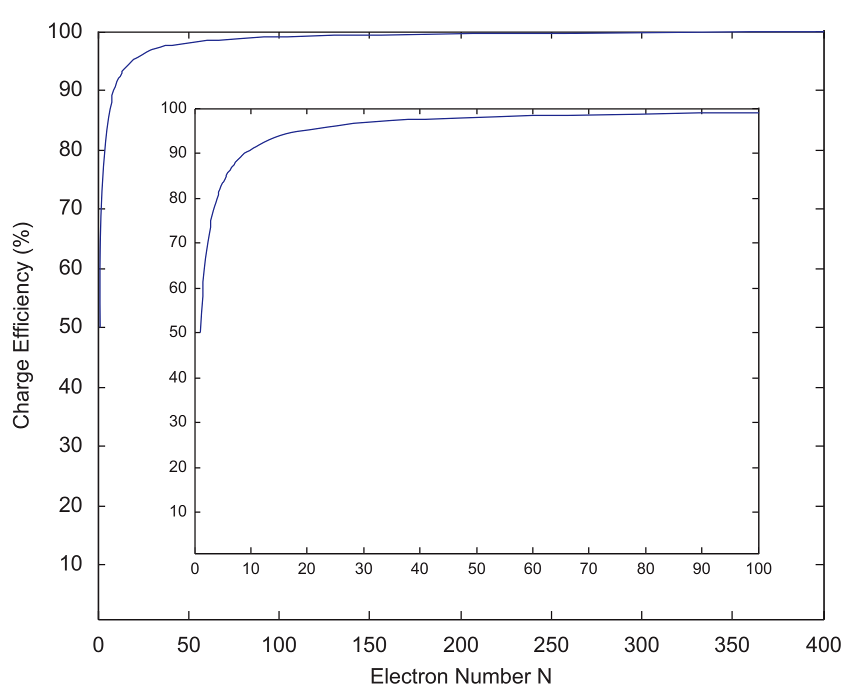

Fig. 2. The curve of charging efficiency with increasing electron number.

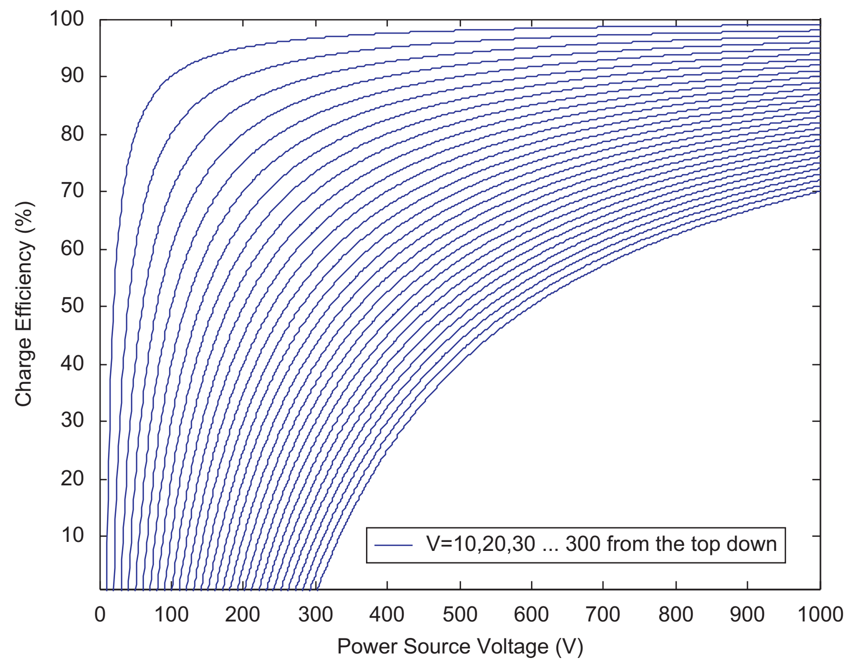

Fig. 3. The efficiency curve at different ΔV with increasing power source voltage.

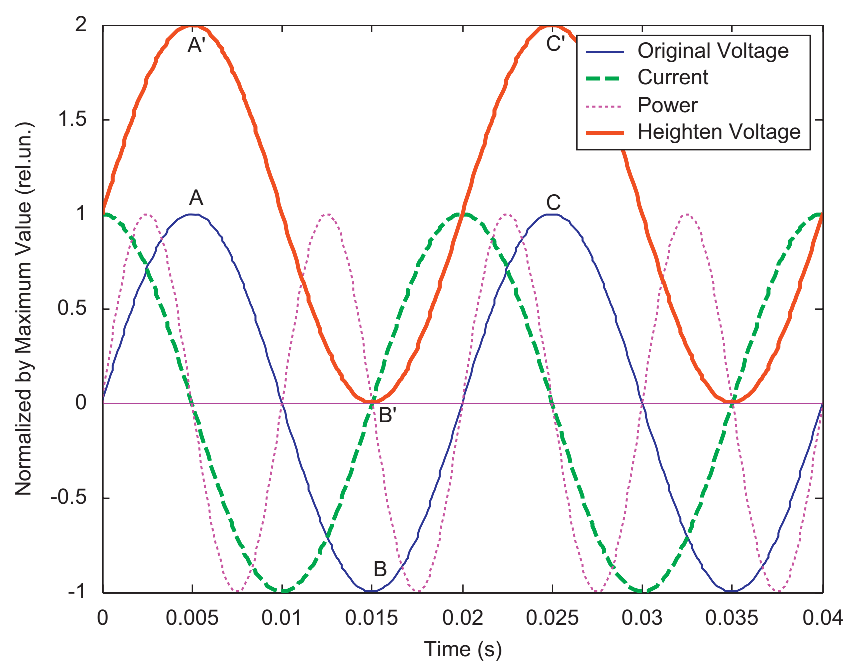

Fig. 4. The voltage waveform of AC power from a power plant, with the addition of one DC voltage and the charge current and power of a storage capacitor.

After voltage heightening, if we select the B′–C′ segment for charging, the current of the storage capacitor will be 0 at the beginning and 0 at the end with a sine wave charging voltage. This will be very advantageous for exerting precision control at the charging end if we need to control the charging voltage of the storage capacitor and minimize the shock to the charging switch and storage capacitor at the beginning of charging. From this point, we designed one new charging circuit for solid-state laser power supply.

4. Experiment

The main circuit of charging and discharging, trigger schedule and charging voltage precision control is analyzed in this section, and the development of a compact charging power source is also introduced in detail.

4.1. Main circuit

Fig. 5 shows the main charging and discharging circuit in the experiment. In Fig. 5, F is the fuse, and C_0 and C are the capacitors for increasing the voltage of the power source and storage capacitor, L is the inductor of the discharging pulse and SCR_1 and SCR_2 are the charging thyristor switch and discharging thyristor switch, respectively. The major working principle is as follows:

1. Capacitor 0 is charged through a soft startup resistor and a diode when the power source is switched on. The soft startup

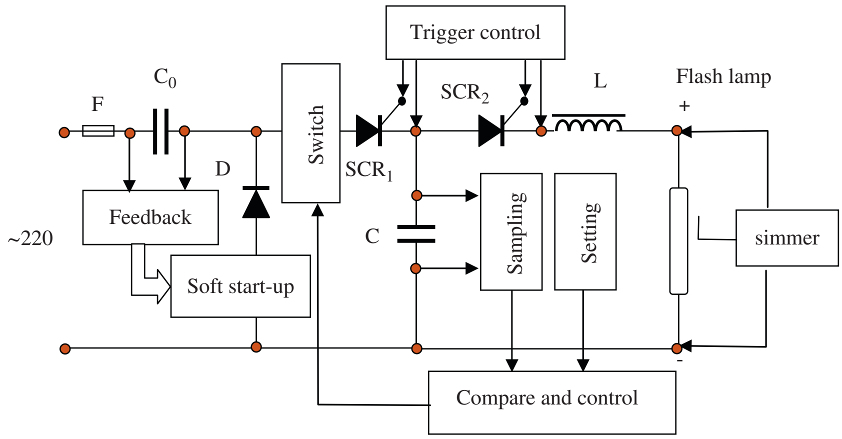

Fig. 5. The main circuit of charging and discharging circuit.

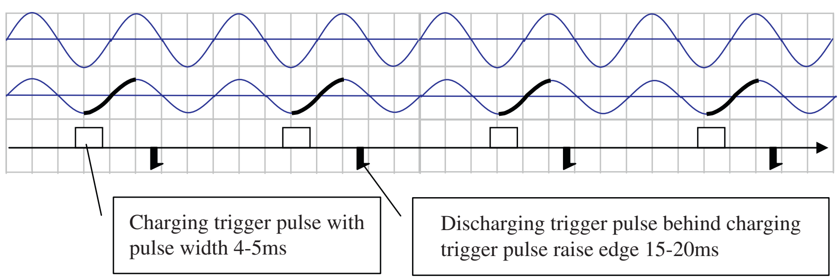

Fig. 6. The synchronous trigger pulse of charging and discharging (the horizontal axis shows the time (5 ms/div), the vertical axis shows the voltage (a.u.), the top waveform shows the power source, the bottom shows the trigger pulse of charging and discharging and the middle waveform shows the charging schedule of the storage capacitor).

resistor becomes shorted when the voltage of capacitor 0 reaches the fixed voltage; the flashlamp is illuminated at the same time.

2. The energy storage capacitor is charged via the power source, capacitor 0, the switch and charging thyristor when the charging thyristor is switched on. The switch is turned off when the voltage of the energy storage capacitor reaches the set value.
3. When the discharging thyristor is switched on, the energy stored in the energy storage capacitor is discharged to the flashlamp through discharging thyristor and inductor L.

The charging process and storage capacitor's voltage will be affected by the capability of capacitor 0. In this charging circuit, the rise period of 10 ms is used for charging the storage capacitor, which is left unused for a period of 10 ms. Therefore, the capacitor 0 was introduced as a replacement compared with using one large battery or a heavy transformer to increase the power source voltage; it can make the laser power supply have advantages such as being compact, low cost, stable and reliable.

When the laser power supply is first switched on, the capacitor 0 is empty, and so we need to charge it first; it will reduce the same electron as the storage capacitor increases, and it must have enough capacity to enable it to have invariableness voltage. In this research work, the storage capacitor is 100 μF, and we chose 2200 μF for capacitor 0; it will yield a very large peak current with no resistor on starting the laser power supply and it may impact the diode D and capacitor 0, but if there is one large resistor, it will consume power. Thus, we only allow the resistor to work for about 10 s when the laser power supply is switched on, and before the laser fires for the first time the resistor is shorted and turns off. Subsequently, about 310 V will be stored in capacitor 0, and so the peak current is much lower than that for the first charging as only the storage capacitor must be charged each time. It will minimize the impact on diode D and capacitor 0, and induce power wastage.

4.2. Trigger schedule

AC power from a power plant is used directly as a power source, and so the AC frequency determines the maximum repetition rate of the laser output. The repetition rate of laser can be adjusted to the required value at below the maximum when a synchronous trigger pulse for charging and discharging is used.

The synchronous trigger pulse of charging and discharging at 25 Hz is used as an example in Fig. 6. For charging a trigger pulse, a wide-charging trigger pulse can be used to attain perfect charging for a storage capacitor, that is to say, the charging thyristor can be switched on ahead of the power source voltage reaching 0, and the storage capacitor will be charged when the voltage reaches 0 and higher about 2 V (the cable and thyristor voltage drop) than the storage capacitor. As we know, the voltage of the storage capacitor usually has about a 10–20 V residual after discharging; the power source will charge the storage capacitor only when its voltage is higher than that of the storage capacitor. Therefore, a wide trigger pulse will be useful. To discharge the trigger pulse, the proper discharging time is important to have a good laser output; we should choose it when the charging is finished and the charging thyristor switch is shut off.

The interval of the discharging trigger pulse should be taken care of for a random trigger, and to ensure no charging trigger pulse can be used after a few milliseconds of discharging trigger pulse. For a 50 Hz AC power source, one pulse with a 7.5 ms width was used to block the charging trigger pulse, ensuring no charging occurred when discharging in our experiment, and one pulse with a 40 ms width to block the next discharging trigger pulse to ensure that the charging finishes. Therefore, the frequency rate can be adjusted freely when the interval of the discharging trigger pulse is larger than 40 ms. The basic discharging trigger schedule and charging period of time are shown in Fig. 7.

In the figure, the up arrowhead shows the discharging time, the catercorner arrowhead displays the charging period of time; one pulse with a 7.5 ms width is used to block the charging trigger pulse after the discharging trigger pulse, and the interval of discharging trigger pulse is 40 ms. In this research work, only a synchronous trigger pulse for charging and discharging was focused on.

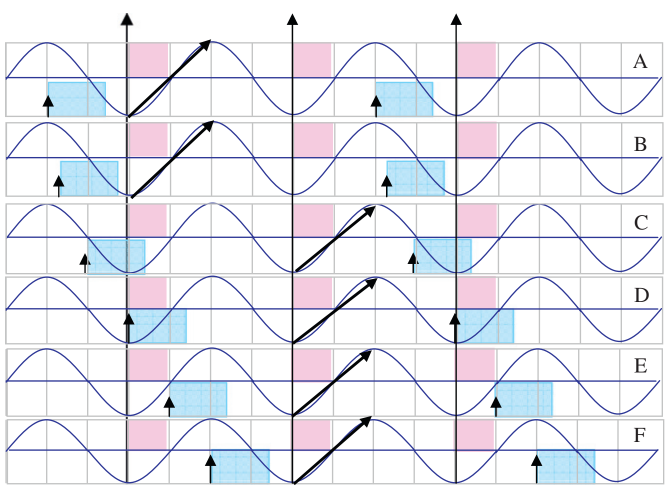

Fig. 7. The discharging trigger schedule and charging period of time at random trigger (the horizontal axis shows the time (5 ms/div), the vertical axis shows the voltage (a.u.) and A–F show six typical schedules of charging and discharging).

4.3. Charging precision

In order to obtain a stable laser output, the coherence of the storage capacitor voltage must be assured. Therefore, the charging precision should be controlled carefully.

One switch before charging the thyristor was used for shutting off the charging current (shown in Fig. 5). This switch is usually open, the storage capacitor will be charged when the charging thyristor is switched on and the switch will be shut off when the capacitor's voltage reached the settings. The charging thyristor will switch off due to the open circuit, and the switch will reopen and await the next charging time.

Generally, the charging precision is determined by measuring the accuracy, the switch dithering time (ΔT) and the rate of voltage change (dv/dt) at the time of shutoff, if the stability of power source is neglected. The charging precision A can be expressed as

$$A = 1 - \frac{\Delta T \cdot (dv/dt)}{V_S} \tag{1}$$

V_S is the setting voltage; if we set $F(t) = dv/dt$, then

$$A = 1 - \frac{\Delta T}{V_S} F(t) \tag{2}$$

In Eq. (2), a high charging precision will be attained at a lower dithering time and rate of voltage change. Fig. 8 shows the curve of the voltage change rate and the voltage of the power source in charging. The lower voltage change rate is present at the setting value near the peak of the power source.

5. Results and discussion

5.1. Waveforms of charging and discharging

A prototype laser power supply based on the concept described above was constructed and a very stable laser output was obtained. In the experiment, the power source voltage is increased

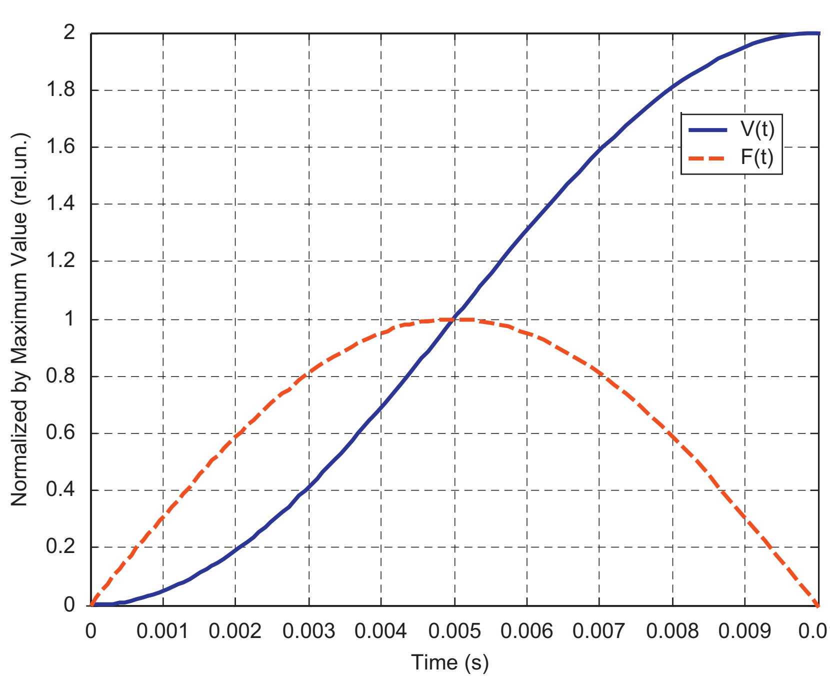

Fig. 8. The curve of the voltage change rate and power source voltage.

to AC 250 V from AC 220 V, the maximal frequency rate reached 25 Hz and the maximal voltage 707 V, in theory. The waveform of charging and discharging at the storage capacitor was recorded with a TDS220 oscilloscope. Channel 1 and Channel 2 were used for recording the power source waveform and the charging/discharging waveform of the storage capacitor, respectively.

The two waveforms appearing at the same time indicate the characteristics of the storage capacitor voltage following a power source; the 'potential drop' and the low energy loss can be read. Fig. 9(a)–(d) shows the waveforms of charging and discharging at 25, 12.5 and 6.25 Hz and a single waveform of discharging, respectively.

In Fig. 9, zero voltage is indicated by the downward arrow, the continuous waveform represents the change of charging power source, and its magnitude is the voltage of capacitor 0 and alternating current together. As one example, the result of repetition rate at 12.5 Hz was analyzed.

The repetition rate is a quarter of 50 Hz and can be deduced from the waveform in Fig. 9(b), because every four charging power source waveform follows one charging and discharging waveform. The capacity of capacitor 0 is 22 times that of the storage capacitor; when the storage capacitor charging finishes, the capacitor 0 will reduce the same energy. About 5% energy transfer occurs from capacitor 0 to the energy storage capacitor in the process of charging; therefore, the peak value of the charging power source waveform with charging and discharging is lower than others. That is to say, the storage capacitor peak voltage cannot reach the maximum theoretical value, and it will be lower than the power source maximum value. The charging waveform is fixed on a level when the storage capacitor voltage reaches the settings, and the two waveforms are difficult to separate from each other. Thus, low energy loss occurs in the charging process.

Compare Fig. 9(a)–(c) with one another; it is not difficult to see the power source waveform zero below 0 V, and it is very clear that the power source voltage cannot reach the maximum voltage 707 V (it should reach at our sampling case) with an increase in the repetition rate. This is because capacitor 0 transfers equivalent electron to the storage capacitor, and it needs definite time charging to capacitor 0 after the energy transfer, and the charging time is directly proportional to the capacitor's capacity. Therefore,

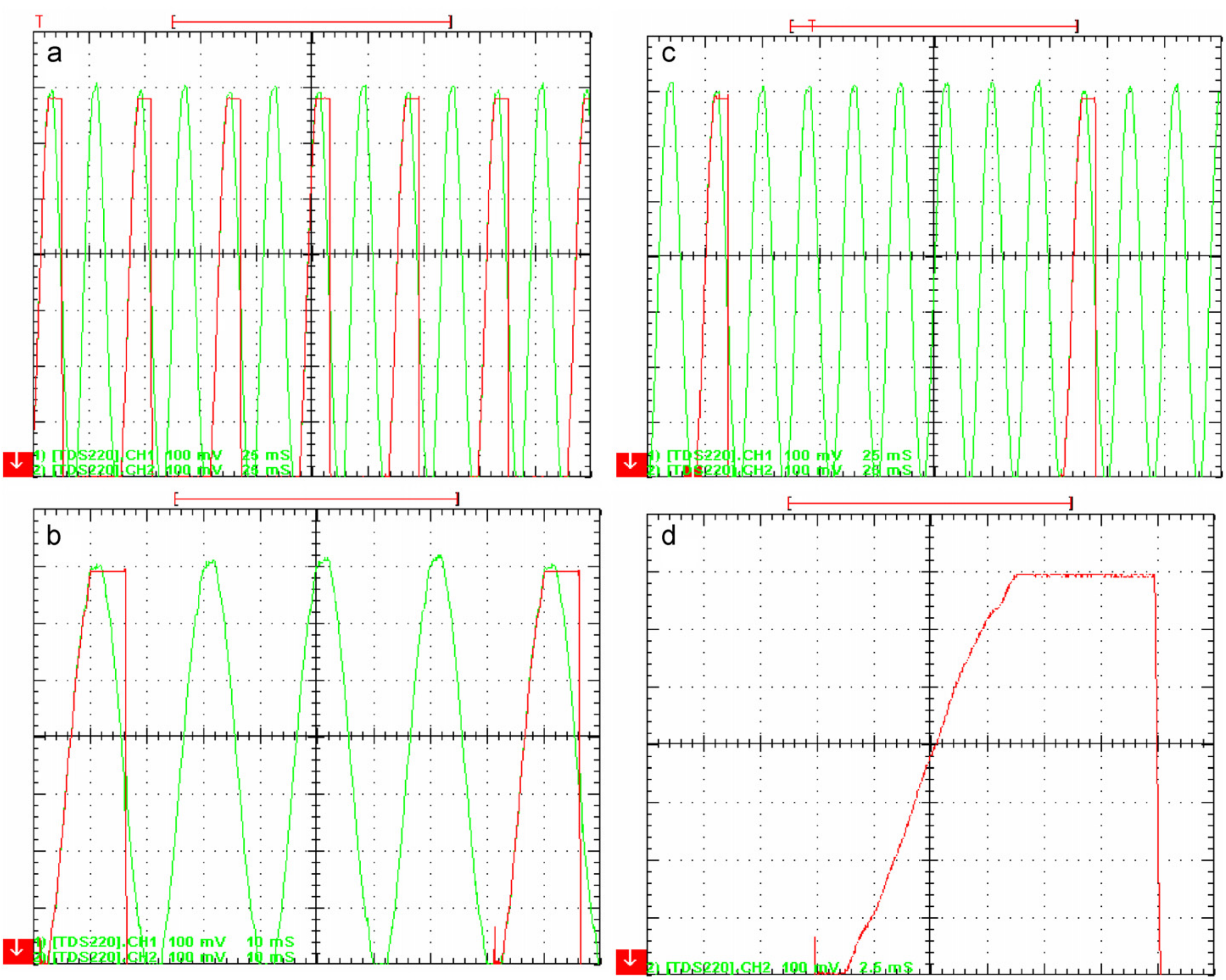

Fig. 9. The waveforms of charging and discharging at (a) 25 Hz, (b) 12.5 Hz, (c) 6.25 Hz, and (d) single waveform of discharging. (Channel 1 and Channel 2 indicate the power source, charging and discharging waveform of the storage capacitor, respectively. The horizontal axis shows the time (ms), and the vertical axis shows one in a thousand of real-value voltage (mV)).

the resistor, about 18 Ω, can be calculated in the charging circuit of capacitor 0.

The charging and discharging waveform at 12.5 Hz is shown in Fig. 9(d). The voltage reached the set value at about 8.75 ms, and was held for about 6 ms for the discharging trigger pulse to arrive. One small spiny pulse at the beginning of charging waveform can be found and the voltage rise after this pulse 1 ms may be caused by discharging of the storage capacitor to capacitor 0 and the power source, because there is about 10–20 V residual voltage in the storage capacitor after discharging the flashlamp. As we know from the above analysis when the power source reaches zero, not really 0 V (it below 0 V), and the charging thyristor switch has been switched on, the storage capacitor will discharge the power source and capacitor 0, and will remain at 0 V, until there is a power source voltage higher than 0 V and over the charging thyristor potential drop of about 2 V, the power source will start charging to the storage capacitor. It has a different holding time usually at a high repetition rate although it is not desired; therefore, it should be avoided by choosing the proper capacity of capacitor 0, storage capacitor, laser repetition rate and the time of charging trigger pulse in practical applications.

5.2. Charging precision

In this laser power system, the real-time voltage was measured and compared with the settings; the results are listed in Table 1.

The maximum relative standard deviation is 0.0032, which means we can almost obtain the same voltage with the charging storage capacitor. Therefore, it has a high charging precision in the experiment. The charging error will be smaller if we can improve the measurement and the display of setting values more accurately.

5.3. The method to heighten the charging voltage

In a storage capacitor 620 V can be obtained when AC 220 V is used as a power source with our design of the charging circuit, although it reaches the lower limit in a solid-state laser. For practical applications, how to increase the voltage of storage capacitor is the key point in future research works; three feasible cases are briefly analyzed.

The first case is similar to a voltage doubler circuit with an AC 220 V, 50 Hz power source; the schematic diagram is shown in Fig. 10.

In Fig. 10, C_0 and C_1 are the electrolytic capacitors with a large capacity, D_1 and D_2 are diode rectifiers, SCR_1 and SCR_2 are charging thyristor switches, C_2 and C_3 are the storage capacitors and SCR_3 is the discharging thyristor switch.

The work steps are listed below.

1. Turn on the power source switch, charging to C_0 and C_1 firstly.
2. Let SCR_1 and SCR_2 switch on at a power source with zero and maximum voltage like B′ and C′ points in Fig. 4(b), charging C_2 and C_3.
3. Switch on discharging thyristor switch SCR_3 at a certain proper time, C_2 and C_3 will be discharging in series to the lamp and the discharging voltage will be two times that found in the above research.

The second case is similar to a voltage tripler circuit with an AC 220 V, 50 Hz power source; it is more complex compared to the first case. Fig. 11 shows the power source phase change.

The schematic diagram of this case is shown in Fig. 12(a)–(d). Here, only the charging circuit is shown. C_0 and C_1 are the electrolytic capacitors with a large capacity, D_1 and D_2 are diode rectifiers, SCR_1 and SCR_2 are charging thyristor switches and C_S is the storage capacitor.

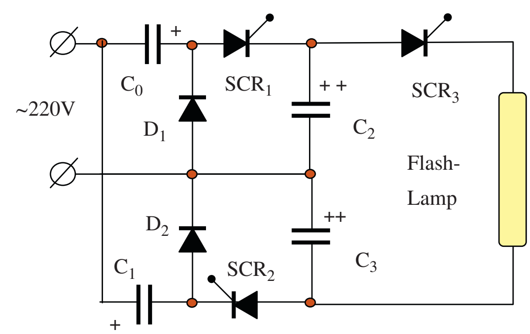

Fig. 10. A schematic diagram of double charging voltage.

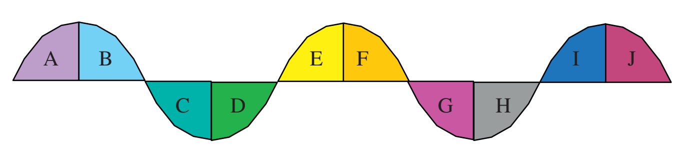

Fig. 11. The power source phase change.

Table 1
Voltage fluctuations of storage capacitor in the experiment (unit: V)

Setting values (V_S)	700	650	600	550	500	450	400
Measure 1	704	651	601	550	499	448	397
Measure 2	705	652	600	551	500	448	396
Measure 3	703	654	601	551	499	447	395
Measure 4	699	653	601	548	498	445	396
Measure 5	702	651	599	549	500	449	397
Measure 6	703	652	601	550	501	448	396
Measure 7	701	652	602	551	497	445	395
Measure 8	705	651	600	547	499	447	397
Measure 9	702	652	599	549	498	449	395
Measure 10	704	652	600	551	499	448	396
Average of measured values ($\bar{V}_M$)	702.8	652	600.4	549.7	499	447.4	396
Charging error ($\bar{V}_M - V_S$)	2.8	2	0.4	−0.3	−1	−2.6	−4
Standard deviation (SD)	1.8738	0.9428	0.9661	1.4181	1.1547	1.4298	0.8165
Relative standard deviation (RSD)	0.0026	0.0014	0.0016	0.0025	0.0023	0.0032	0.002

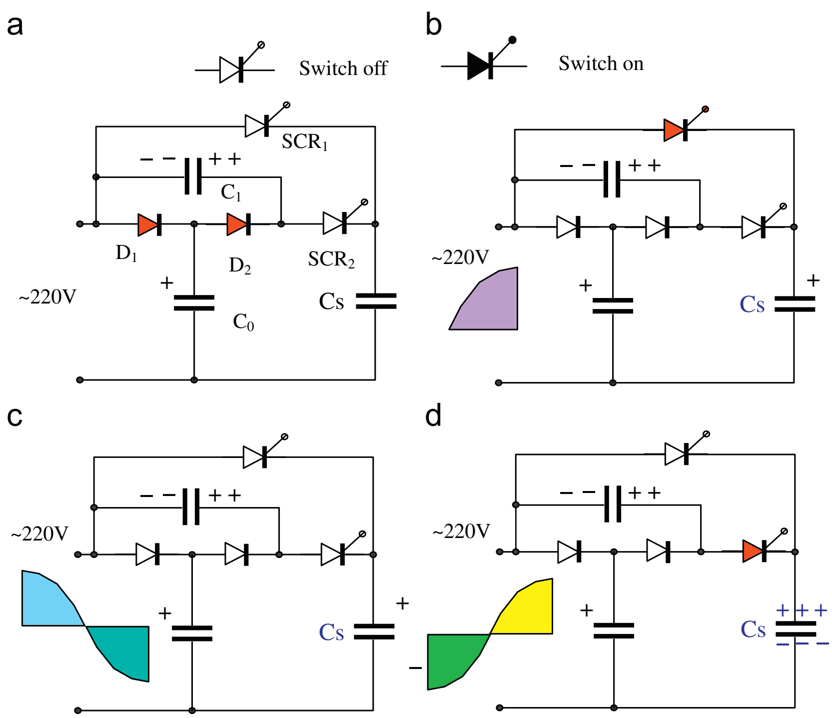

Fig. 12. A schematic diagram of a triple voltage circuit, (a) voltage doubler circuit finished, (b) charging single voltage to storage capacitor, (c) awaiting the zero arrival and (d) charging triple voltage to the storage capacitor.

The main steps for work are listed below. The charging process was divided into a preliminary step and five phases according to the phase change in Fig. 11.

1. Preliminary step; turn on the power source switch, charging to C_0 and C_1 to a single and double voltage through diode rectifiers D_1 and D_2, that is to say, it should let voltage doubler circuit charging finish firstly (shown in Fig. 12(a)).
2. The first step: when the power source waveform reaches the *A* phase shown in Fig. 12(b), switch on charging thyristor switch SCR_1, charging single voltage to storage capacitor C_S.
3. The second and third steps: the charging circuit at a waiting period 10 ms, that is the power source *B* and *C* phase, shown in Fig. 12(c). The charging process awaiting the power source voltage reaches zero.
4. The fourth and fifth steps: charging triple voltage to storage capacitor C_S in the power source *D* and *E* phase, shown in Fig. 12(d). Switch on charging thyristor switch SCR_2 at power source zero; as we know, the storage capacitor C_S has been charging the single voltage in the first step, and the potential drop at SCR_2 on both sides will be 0 when the power source zero through capacitor C_1 after the voltage heightens, and the voltage of storage capacitor C_S will be charging to triple voltage at the end, and the repetition rate can reach 25 Hz.

The last optional case uses an AC 380 V, 50 Hz power source; the basic principle is shown in Fig. 5. Two different terms are compared using an AC 220 V, 50 Hz power source that we have tested. One is the time of the trigger pulse of charging and discharging and the other is different ground between the flashlamp and the storage capacitor; hence they must receive attention when using this case. In a practical application, we can use two or more storage capacitors discharging to obtain a higher repetition rate.

6. Conclusions

In this research work, a new explanation based on physical theory is introduced which gives a brief concept for achieving high efficiency in a charging circuit, and the charging efficiency at different potential drop was computed. A prototype power supply for pulsed YAG lasers is implemented successfully. The details about how to achieve the charging power source, the operation of the new laser power supply (including the main circuit, the trigger schedule of charging/discharging and the charging precision) and how to improve the charging voltage and increase the repetition rate were discussed. Finally, the experimental results of waveforms of charging/discharging and the charging precision were analyzed and summarized. Compared with traditional pulsed laser power supply, the new proposed system possesses better performance in the features of efficiency, compactness, stability, reliability and charging voltage precision.

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