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**PULSED ELECTRODELESS DISCHARGE AS A LIGHT SOURCE
FOR LASER EXCITATION AND OBSERVATION OF THE
CHARACTERISTICS OF LASER OUTPUT**

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**Foreign Technology Division
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By: Chang Zung-kui and Yeh Mow-foh

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ABSTRACT: The authors conducted an experiment to study the characteristics of electrodeless discharge tubes for use in ruby and Nd-glass laser operation. A discharge loop composed of a high-voltage low-inductance capacitor, a 2-3 μ h primary inductance coil with multiple turns, and a coaxial quartz discharge tube was used. The discharge tube was filled with xenon or argon at 10 mm Hg or more. Discharging period was found to be 10 μ sec or more using a type MY-50-3 capacitor of 0.2 μ h internal inductance. The period can be decreased with a type MY-110-0.022 capacitor. Emission spectra of discharge tubes at various pressures and voltages were obtained with a quartz spectrograph. Analysis was made for emission spike, frequency mode, quasicontinuous damped oscillation, and threshold value of laser output. Application of electrodeless discharge tubes to lasers led to the following conclusions: 1) high-energy input is possible in discharge tubes; 2) repetition frequency of lasers is raised; 3) higher pumping efficiency with higher power can be achieved; 4) the discharge tube has a longer service life; and 5) emission spectra can be matched with absorption bands of various laser materials. Thanks are extended to Sun Hsiang (1327/3276) for helpful suggestions, to Yao Chin-chen (1202/6651/3791) for treating the discharge tube, to Hsu Chi-jen (1776/4480/0088), She Yung-po (0152/3057/2672), and Chang Yu-lung (1728/2589/3891) for assistance, to Chang Lo-hui (1728/2867/0000) for supplying ruby materials, and to the Peking Architectural

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Engineering College (Pei-ching chien chu kung ch'eng hsueh yuan) and the Peking Glass Institute (Pei-ching po li yen chiu so) for supplying Nd glass samples. The authors are deeply indebted to counsellor Chang Chih-san (1728/1807/0005) for encouragement, support, and guidance. Orig. art. has: 9 figures. English translation: 13 pages.

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PULSED ELECTRODELESS DISCHARGE AS A LIGHT SOURCE FOR LASER EXCITATION AND OBSERVATION OF THE CHARACTERISTICS OF LASER OUTPUT*

Chang Zung-kui and Yeh Mow-foh

(Academia Sinica)

ABSTRACT

*High voltage pulsed electrodeless discharge in rare gases can be used as a light source for laser excitation.** In this paper, some initial experimental results in this respect are reported. In the first part of the paper, the light source and light output measurements on it are described. The second part is concerned with some investigations of ruby and Nd-doped glass lasers pumped with electrodeless discharge tubes. These investigations include determination of thresholds, observation of spikes, oscillation on single mode and regular damped oscillation. Finally, an analysis of the properties of this type of light source is made. It is considered that these light sources provide a new source of light for the excitation of solid lasers and have a great future in the development of high-energy, high-power and high-frequency devices.*

I. INTRODUCTION

In solid laser technology, the choice of an excitation light source is an important problem. At present, in pulsed solid lasers, the extensively used xenon flash lamp has some prominent advantages, such as high efficiency in the transformation of electrical to luminous energy and relatively good matching of the emission segment with the absorption spectra of some of the materials most important in making solid lasers. Consequently, it has gained broad application in various devices. Even though this is the case, these flash lamps still have their drawbacks. For example, when voltage is raised in use and the input energy is high, the lamp tube is easily damaged, the electrode readily turns black and functioning is not stable enough. In addition, the large amount of heat radiated by the flash lamp is also harmful to laser materials.

Consequently, the search for a new light source to overcome the above defects of the flash lamp is of tremendous significance in the development of laser technology. It appears that the use of high-voltage condensers in an energy-storing light source has advantages in many areas. There are two methods available for high-voltage pulse discharge to produce emission of light from isoionic bodies. One is discharge through discharge tubes with electrodes. This method has already been proposed as a light source for laser

excitation [1]. Up to this date, there has not been any significant development in this method. The other is to make use of induced discharge in an electrodeless discharge tube. This is similar to the apparatus used in the study of high-temperature angular contraction (θ -compression) of isoionic bodies. In order to excite lasers, the discharge tube can be made in the form of coaxial cylinders. The advantages of this coaxial excitation light source have been discussed in Reference [2]. In addition, the electrodeless light source has other advantages for laser excitation, for example, short duration of flash, easy manufacture, ability to take higher energy input, etc. This work is an attempt to make a preliminary report on experimental results with this type of electrodeless discharge. The first part of this article deals with a description of the characteristics of the light source and experimental conditions. The latter part presents experimental results from the use of electrodeless discharge in the pumping of ruby and Nd-doped glass lasers. Some of the results obtained reflect the characteristics of the light source itself. This appears to be of great significance to research on the light-emission process of solid lasers and the development of new light sources.

We have seen preliminary reports in the literature [3] on the use of electrodeless argon discharge to pump ruby lasers, which has since been developed into high-repetition-frequency devices and oscillation amplifiers [4, 5].

II. LIGHT SOURCE

1. Experimental Apparatus

The discharge circuit is composed of a high voltage low inductance pulse capacitor, a primary induction coil and a coaxial cylindrical discharge tube (as shown in Fig. 1). When the condenser discharges to the induction coil across the ball gap, an in-

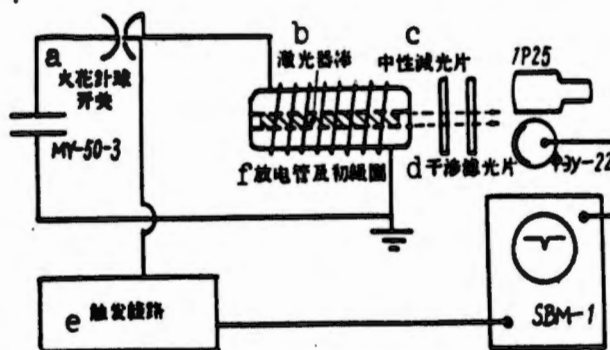


Fig. 1. Schematic diagram of experimental apparatus. a) Ball gap; b) laser rod; c) neutral compensation plate; d) interference filter; e) ignition circuit; f) discharge tube and primary coil.

stantaneous pulse current of several tens of thousands of amperes passes through the induction coil, inducing in it a transient electromagnetic field which penetrates through the gas in the discharge tube, thereby producing flashes.

The pulse condenser is a type MY-50-3, capacitance 3 μf , voltage 50 kv, internal inductance 0.2 μh . In order to reduce the energy loss in the external discharge circuit, and to increase the efficiency of energy transformation, it is necessary to reduce the circuit inductance to a minimum and to increase the inductance of the primary coil at the same time. Hence we did not use the single-coil form of the conventional θ -compression device in this work but instead a multicoil inductor. This is a departure from the single-coil experimental apparatus as described in References [3, 4, 5]. Our experience indicates that the use of a multicoil inductor may increase the quantity of input energy and also the energy transfer efficiency.

The inductance of the coil is 2-3 μh . The discharge cycle is 10+ μsec . In a low energy apparatus, if a type MY-110-0.022 pulse condenser is used (capacitance 0.022 μf , voltage 110 kv), the discharge cycle would be still shorter, hence the light emission period of the discharge tube would also be shorter. Utilizing this type of arrangement, it is possible to conduct laser experiments with special objectives.

The discharge tube is a coaxial quartz tube filled with xenon or argon at ten to one hundred mm Hg. When the gas pressure rises, the ignition voltage also rises. The outside diameter of the discharge tube is 3-4 times the inside diameter. The outer wall of the discharge tube is coated with powdered magnesium oxide as a diffuse-reflecting layer. This increases the stimulation efficiency of the laser by 35-40%; at the same time, the discharge tube is close-coupled to the primary induction coil to avoid loss of the electromagnetic energy in the coils. The dimensions of the discharge tube match those of the laser materials. Under ordinary conditions, the discharge tube is slightly longer than the rod of laser material, so that the entire rod can be uniformly illuminated.

2. Characteristics of the Light Output of the Discharge Tube

(1) Measurement of the Spectrum

Using a quartz spectrograph, the emission spectra of two gases (xenon and argon) were photographed under various gas pressures and at various voltages in the discharge tube. These spectra were compared with those of the xenon flash lamp. The following points may be drawn as conclusions from the results (Fig. 2):

(1) When the gas pressure in the discharge tube changes while all the other parameters are maintained constant, there is no prominent change in the spectral intensity. But when the voltage at discharge is raised, the spectrum of the high gas pressure discharge tube is higher in intensity than that of the tube with low gas pressure.

(11) Under conditions of equal gas pressure inside the discharge tubes we see from comparison of the emission spectra of argon and xenon that the spectrum of argon is more intense than that of xenon in the near ultraviolet region; in the green region (this is the main absorption region of ruby and Nd-doped glass) the spec-

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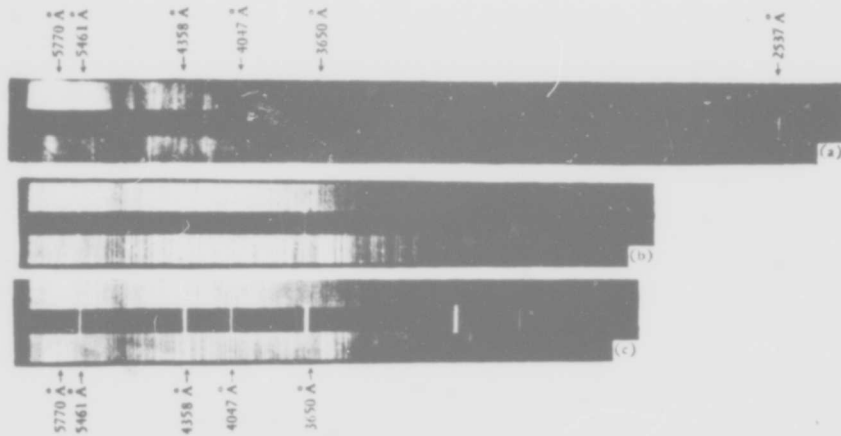


Fig. 2. (a) Spectra of xenon-filled discharge tube and xenon flash lamp. Top: flash lamp (200 mm Hg, 250 μ f, 2 kv). Bottom: electrodeless discharge tube (30 mm Hg, 3 μ f, 20 kv). (b) Spectra of xenon and argon discharge tubes (10 mm Hg, 3 μ f, 30 kv). Top: xenon. Bottom: argon; (c) spectra of xenon and argon discharge tubes (40 mm Hg, 3 μ f, 30 kv). Top: xenon. Bottom: argon (the center spectrum is the line spectrum of mercury).

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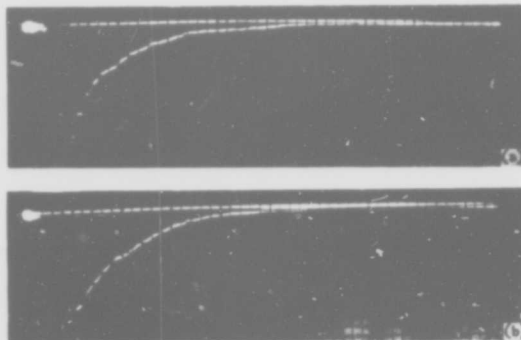


Fig. 3. Oscillogram of light output of xenon discharge tube (3 μ f, 30 kv). (a) 10 mm Hg center wavelength of filter plate 556 millimicrons, scan 500 μ sec; (b) 40 mm Hg, center wavelength of filter plate 580 millimicrons, scan 500 μ sec.

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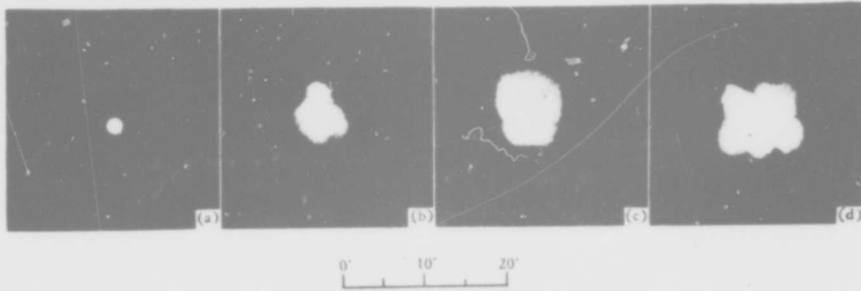


Fig. 4. Far-field patterns of 6 [diam.] x 76 Nd-doped laser. (a) $1.00 \times$ threshold energy input; (b) $1.04 \times$ threshold; (c) $1.07 \times$ threshold; (d) $1.14 \times$ threshold.

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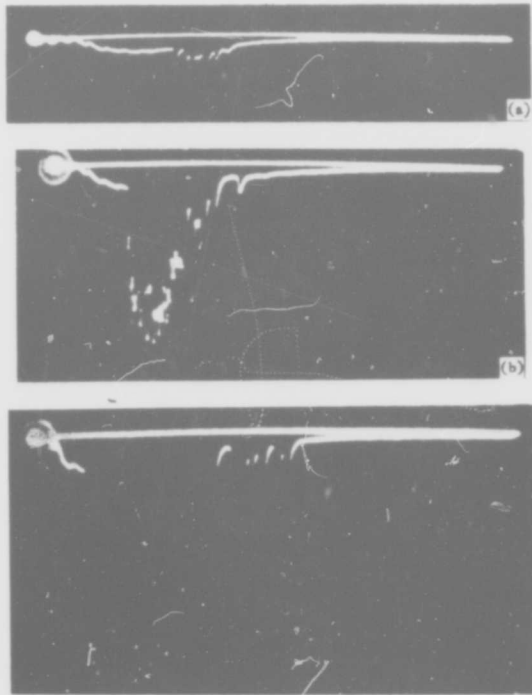


Fig. 5. Output oscillogram of 12 [diam.] x 155 Nd-doped glass laser. (a) $1.08 \times$ threshold energy input, scan 500 μ sec; (b) $1.22 \times$ threshold energy input, scan 500 μ sec; (c) $1.46 \times$ threshold energy input, scan 500 μ sec.

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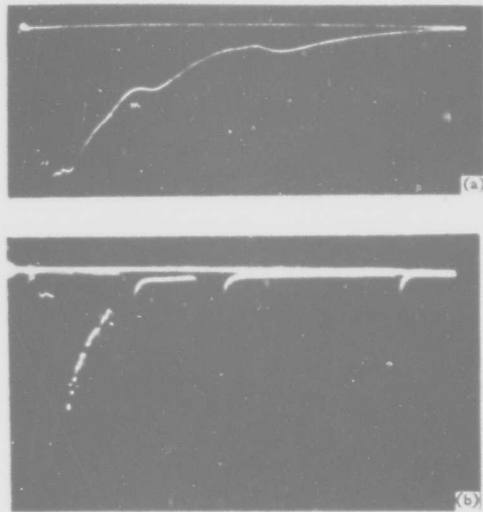


Fig. 6. Output of Nd-doped glass laser and output of discharge tube. (a) Oscillogram of discharge tube light output at 577 millimicrons, scanning 500 μ sec; (b) oscillogram of output of Nd-doped glass laser.

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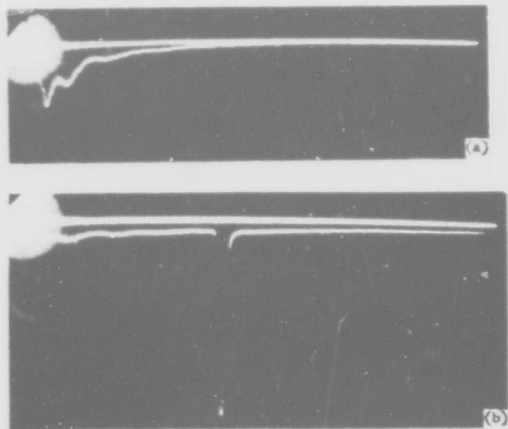


Fig. 7. Oscillogram of the output of 6 [diam.] \times 76 Nd-doped glass laser. (a) Using 580 millimicron filter plate to record the output of the discharge tube, scan 300 μ sec; (b) laser output, scanning 300 μ sec.

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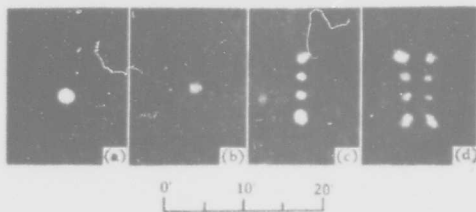


Fig. 8. Far-field photograph of single mode output of Nd-doped glass laser. (a) TEM₀₀; (b) TEM₀₁; (c) TEM₀₃; (d) TEM₁₃.

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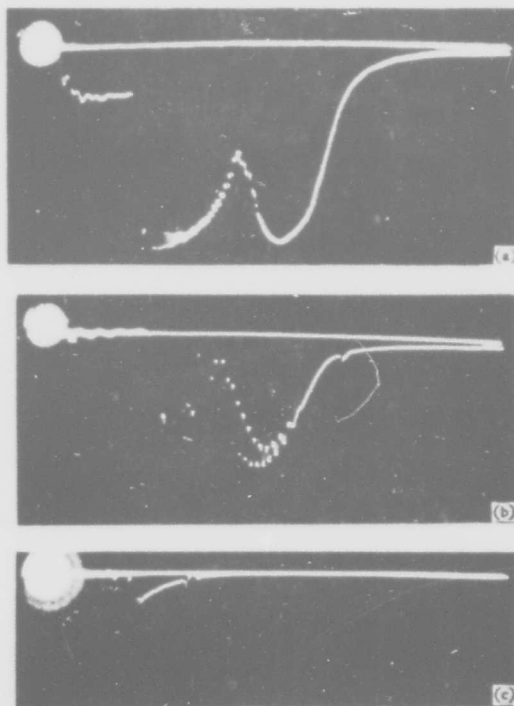


Fig. 9. Damped oscillation of output of ruby laser. (a) 13 [diam.] × 178 ruby laser, 1.3 × threshold input energy, scan 500 μsec; (b) 13 × 178 ruby laser, 1.2 × threshold input energy, scan 500 μsec; (c) 6 × 96 ruby laser, 1.5 × threshold input energy, scan 500 μsec.

trum of xenon is more intense than that of argon. Therefore, during the excitation of an Nd-doped laser, using a xenon discharge tube as the excitation light source, the oscillation threshold is lower than when an argon discharge tube is used.

(iii) On comparison of the spectra of the xenon pulse flash lamp (gas pressure 200 mm Hg) and the xenon discharge tube (gas pressure 30 mm Hg), we find that the spectrum of the xenon flash

lamp is nearly continuous, while that of the xenon discharge tube is principally a line spectrum. Also, in the ultraviolet region, the intensity of the xenon discharge tube is higher than that of the xenon flash lamp.

(2) Characteristics of Photoelectric Oscillograms of Discharge Tube Light Output

In recording photoelectric oscillograms of the output light of the discharge tube, 404.7, 556, 580 and 850-millimicron interference filter plates were used. It is these wave segments that are the principal absorption bands of ruby and Nd-doped glass lasers. The results obtained are as follows:

(i) For these wave segments, the output waveforms and emission times are basically all similar.

(ii) When the gas pressures of the discharge tubes are different, the time characteristics of the output wave form are also different. Under the conditions of low gas pressure, the waveform is narrow and sharp, but when the gas pressure is high, it is broad and low. The waveform peak occurs earlier when the gas pressure is low.

(iii) For given gas pressures of the discharge tubes, the higher the discharge voltage the earlier the appearance of the peak of the waveform.

(iv) For a given energy input, the duration of light emission at high voltage and low capacitance is relatively shorter than that at low voltage and large capacitance.

Figure 3 shows an example of the time characteristic of the output waveforms at 556 millimicrons and 558 millimicrons for two xenon discharge tubes (10 and 40 mm Hg) discharging at 30 kv and 3 μ f.

III. OBSERVATION OF THE CHARACTERISTICS OF THE LIGHT OUTPUT OF LASERS

(1) Oscillation Threshold

1) We conducted the following experiments on ruby lasers. The size of the laser was 13 [diam.] \times 178 (mm).^{*} The surfaces of the two ends were coated with silver. When a straight-tube-type xenon flash lamp with a diffuse reflector is used as the excitation light source, its threshold value is 2600 joules. When a discharge tube is used as the excitation light source, the threshold varies with conditions: when the discharge tube is at a gas pressure of 15 mm Hg, voltage 34 kv, capacitance 6.23 μ f, the threshold is 3600 joules; when the xenon discharge tube is at a gas pressure of 40 mm Hg, capacitance 6.23 μ f, voltage 26 kv, the threshold is 2100 joules. If the gas pressure of the xenon discharge tube remains at 40 mm Hg, while the capacitance is 3.18 μ f and the voltage at 34 kv, then the threshold decreases to 1840 joules. From this, we see that under the conditions of high gas pressure and high voltage discharge, the pumping efficiency of the laser is

slightly increased. This is in agreement with the results obtained in the measurement of the intensity characteristics of the light output of the discharge tube.

2) We also carried out experiments on Nd-doped glass lasers. The size of the Nd-doped glass rod is 6 [diam.] × 76 (mm),* both ends coated with silver. When a flash lamp is used as the excitation light source, the threshold is 110 joules. Under the conditions of using a discharge tube as the excitation light source, with capacitance at 0.236 μf (by combining 10 MY-110-0.022 capacitances in parallel) and voltage at 34 kv, the threshold is 136 joules. When the input energy is increased, the far-field spots of the output radiation gradually increase in size, as illustrated in Fig. 4. This result is also similar to those obtained with the conventional flash lamp.

From the above experimental results, one can see that when a high voltage electrodeless discharge tube is used as the light source for lasers, with the present experimental conditions, its effect is comparable with the conventionally used flash lamp.

(2) Observation of Spikes

1) In the experiments on Nd-doped glass lasers, the size of the glass rods was 12 [diam.] × 155 mm and the surfaces at both ends were coated with silver. When the input energy is gradually increased, there is very little difference in the conditions of appearance of spikes when compared with the case of using the flash lamp as the excitation light source (see Fig. 5). But the time when oscillation starts is, however, slightly earlier than in the case of the flash lamp. Besides, with the increase in the energy input, the initiation of oscillation also comes about earlier and earlier. At an energy input of 1.5 times the threshold, less than 50 μsec from the beginning of discharge, oscillation is observed.

2) Under certain conditions of discharge, such as when the discharge tube is relatively large in size and has a relatively low gas pressure, there appear several maximum values of the light output of the discharge tube: thus in the output of the laser the spikes observed are also divided into several groups. This phenomenon is shown in Fig. 6.

3) In low-energy devices (capacitance 0.236 μf , voltage 34 kv), a time delay of the spike is observed in Nd-doped glass lasers. The emission time of the xenon discharge tube (gas pressure 20 mm Hg) is about 40 μsec , whereas oscillation of the laser begins after 130 μsec (Fig. 7). In [3], the appearance of the output spike in a ruby laser was observed to lag behind the output of the discharge tube by about 100 μsec . But this phenomenon had never been observed in the case of Nd-doped glass lasers. It is believed that the oscillation lag in ruby lasers is due to spatial nonuniformity in emission from the excitation light source, since a single-coil excitation discharge tube was used in their experiments. The width of the coil was only one-eighth the length of the ruby rod. At the instant of discharge, the light of the excitation source was concentrated mostly in the vicinity of the coil; hence

there was not sufficient illumination at the two ends of the ruby rod. Thus, it appears as if there were a Q-modulation action on the ruby. Not until the fluorescent energy from the center of the ruby has had sufficient time to transfer to the two ends, thereby reducing their absorption coefficients, could there be output from the laser. This then requires a certain amount of time; hence the phenomenon of the delay in the appearance of the spikes. As for Nd-doped glass lasers, since they are of the four-level system, such phenomena are absent.

But in our experiments the primary is multicoiled. The illumination on the glass rod is uniform; hence the causes of the delay phenomenon do not exist. In the output of Nd-doped glass lasers, however, a spike-delay phenomenon was nevertheless observed. The phenomenon could even be reproduced several times. Hence we cannot consider the explanation offered in [3] as satisfactory. We feel that elucidation of the mechanism of this phenomenon will require further research.

(3) Single-Mode Oscillation

Since it is possible to stabilize control of emission conditions by this type of arrangement, it is also possible to regulate the laser oscillation threshold precisely. Taking advantage of this feature, we obtained a series of single-mode far-field patterns for a series of Nd-doped glass lasers. These patterns were recorded directly by the use of a 1P25 phase-converter tube. These patterns are in agreement with those theoretical expected and also with the results obtained by other investigators [6]; at the beginning of oscillation, the most easily discerned pattern is $TEM_{0,0}$ or $TEM_{0,1}$. Figure 8 presents illustrative examples of a few single-mode photographs. Ordinarily, in order to observe single modes in the output of pulsed solid lasers, it is necessary to use time-resolved photography.

(4) Observation of Quasicontinuous Regular Damped Oscillations

In observations of the output spikes of ruby lasers (the two ends of the ruby laser polished and silver coated), when the input energy has more than 1.2 times the threshold, we found a series of quasicontinuous regular damped oscillations (Fig. 9). In the past year or so, many other investigators have also observed and studied this effect [7-13]. The consensus is that to obtain this type of regular damped oscillation, special considerations must be made regarding the structure of the resonance cavity [13] or some other necessary equipment must be added [8]. In the conclusions of [10-12], it was also considered that the output of the excited light from the ruby laser and its time relationship depend largely on the structure of the resonance cavity; hence when they were investigating this type of regular damped oscillation, they all employed a resonance cavity having an external spherical reflector.

In our experiments, the conditions were different. We used a silver-coated plane-parallel resonance cavity. In this type of resonance cavity, there is no mode degeneration, but regular damped oscillation has been observed in it. We believe that this could be associated with the special light source used in our ex-

periments. The emission times of high-voltage electrodeless discharge light source are shorter than those of the conventional flash lamp. Its instantaneous light output power could be higher than that of the ordinary flash lamp by one order of magnitude. It seems that this type of regular damped oscillation is related to a relatively higher rate of excitation in this type of light source. When the input energy decreases, the regular damped oscillations become separate spikes with relatively higher amplitudes.

In experiments on Nd-doped glass lasers, regular damped oscillations were not observed using the plane-parallel cavity.

IV. PRELIMINARY CONCLUSIONS

The preliminary investigations reported indicate that the pulsed electrodeless discharge light source possesses at least the following advantages for lasers:

1) The discharge tube has no electrodes: therefore the input energy could be higher, which is useful in the design of high-energy lasers. Concerning experimental work in designing high-energy electrodeless discharge devices, it has already been greatly advanced in physical research on isoionic solids; for example, the angular compression device used to control thermonuclear reactions already has a total energy storage capacity reaching 3,500,000 joules [14].

2) The thermal radiation of the discharge tube is low, and the heating action it has on the laser material is not as pronounced as that of the flash tube. Consequently, it could be used to build lasers with high repetition frequency. At normal temperature, it has at present reached 60 sec^{-1} [5].

3) The light emission time of the light source is very short. The efficiency and power of the pump are both high. This is advantageous to laser material having a short lifetime of fluorescence. If this is combined with the technique of Q-modulation, it could be still more advantageous in the building of high power lasers.

4) Filling the discharge tube with a suitable gas or gas mixture in definite percentage compositions could match the emission spectrum exactly to the absorption bands of various laser materials.

5) The lifetimes of these light sources are long. According to the report in [5], discharge tubes that have been in use for sixty thousand cycles show no noticeable change in their light emission efficiency. This is higher than the lifetime of the conventional flash lamp by two orders of magnitude.

Summarizing what was said, we can see that pulsed electrodeless discharge devices have provided lasers with a new excitation light source. Certainly in order to fully realize their potential and advantages, there are quite a number of problems that need to be investigated still further.

The authors wish to express thanks to Comrade Sung Hsiang for

his helpful advice, Comrade Yau Tsin-tseng for work on the discharge tubes, and Comrades Hsu Tsi-cheng, Zo Yung-po, Chang Yu-long and others for their assistance in the experimental work.

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FOOTNOTES,

1* Received 18 May 1965.

1** In the past (laser) has been translated as "light quantum amplifier," "light emission exciter" or "lai-zer." It has now been standardized to "light exciter."

8 The ruby material was provided by Comrades Chang Ching-sui et al.; we wish to express our gratitude.

9 The Nd-doped glass sample was furnished by the Peking Architectural and Engineering Institute and Peking Glass Research Institute. We express our thanks.