A fast cavity dumper for a picosecond glass laser

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A fast cavity dumper for picosecond glass laser has been made. The optical and electrical characterization of the cavity dumper is described. An avalanche transistor Marx bank generator drives the cavity dumper. Up to 5 kV peak amplitude and 1.5 ns fall time negative polarity step pulses are generated by the Marx bank circuit. With a capacitive load like Pockels cell the pulse fall time increases to 4 ns. Optical switching times as fast as 2 ns (10%–90%) are experimentally measured. The contrast ratio of 1000 is obtained after a double pass through an amplifier. Single picosecond pulses are produced with an energy jitter of 10%.

I. INTRODUCTION

Combined active passive mode locking of solid-state lasers has dramatically reduced the jitter in the pulse energy and pulse duration of picosecond pulses. Single-pulse energies up to 1 mJ at a 100 Hz repetition rate can be obtained with cavity dumping of such lasers.[1,2] The selection of a single picosecond pulse by cavity dumping has certain advantages such as the following:

(1) Higher single pulse energy from the oscillator stage.

(2) Lower laser threshold due to the high Q of the resonator during pulse buildup which is important for increasing the repetition rate.

(3) Reduced optical feedback to the oscillator from other elements of the experimental setup without any additional optical isolators.

(4) The requirement of a step pulse of lower voltage (3.3 kV typically) as compared to a rectangular pulse of 5–10 ns duration with a peak amplitude of 6–12 kV in the case of external pulse selection.

We report in this paper the design and characterization of a cavity dumper made for a Nd:phosphate glass mode-locked laser. A Pockels cell-polarizer combination inside the resonator of an active-passive mode-locked laser acts as a cavity dumper. The Pockels cell is driven by a fast (4 ns) fall time 3.3-kV electrical pulse generated by a Marx bank circuit based on 2N5551 transistors. A specially designed high-voltage attenuator probe was employed to measure the rise time and pulse amplitude of the electrical pulse. A simple procedure for selection of transistors is described. The initial optical characterization of the cavity dumper was performed in the free-running regime of the laser. Optical switching times of 2 ns were experimentally measured. The contrast ratio of 10^3 was obtained after a double pass through an amplifier. The single-pulse output energy obtained from the mode-locked oscillator is restricted to 0.5 mJ due to intracavity optical damage problems.

A similar cavity dumper is briefly described in Ref. 1 for use in a 80-ps, 100-Hz repetition rate YAG laser. The cavity dumper is driven by an avalanche cascade of 2N5551 transistors. A supply voltage of 3.3 kV and a fast 1-ns rise-time trigger signal was required. Our work differs from this paper in the following. A more detailed description of a cavity dumper made for a 6-ps, 0.1-Hz repetition rate glass laser is reported. A Marx generator instead of a cascade based on 2N5551 transistors is used for driving the Pockels cell. It requires only a 900 V supply voltage and is probably electrically simpler. We report the details of electrical and optical characterization and selection procedure for transistors. We also find that slow trigger signal (100 ns rise time) is adequate for reliable operation of the cavity dumper with a jitter of 1 ns. The Marx generator is a modified version of a similar circuit described in Ref. 3 which was based on 2N5550 transistors. It was made for generating 2.5-kV, 2-ns fall-time (open-circuit) pulses to drive "pseudospark switches." We are able to generate up to 5 kV step pulses with 1.5 ns fall time in open circuit and 4 ns fall time with a capacitive load like Pockels cell.

II. ELECTRONICS

A. Transistor selection

The typical cavity round-trip time of a solid-state mode-locked laser is about 10 ns. Fast electrical high-voltage step pulses of 3–4 kV with rise times of 1–4 ns are required for cavity dumping of such resonators. There have been several such circuits described earlier.[3–10] Krytrons are efficient switches which can drive low-impedance loads with subnanosecond jitter and rise times. However, due to large switching delays (and nonavailability in our case) they are not suitable for cavity dumping of mode-locked lasers. The Krytron commutation time can be reduced by employing a fast-rising trigger pulse generated by avalanche transistor stacks. Such hybrid circuits using ZtX304 transistors have been reported in Ref. 4. The all-solid-state high-voltage switches based on transistors operating in the avalanche mode have certain advantages such as stable low EMI operation with short trigger delays and long operating life.

Sufficient information about the transistors operating in the avalanche mode is not available. All transistors are

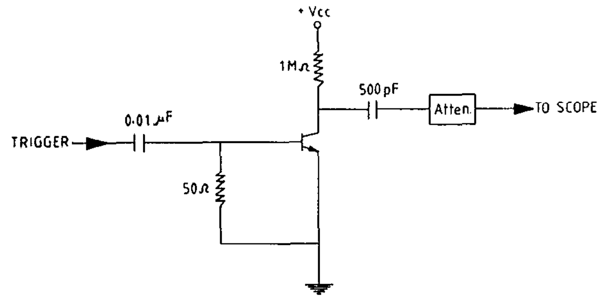

FIG. 1.Testing circuit for avalanche transistors.

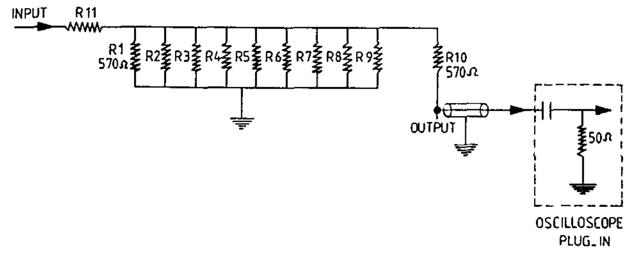

FIG. 2. Electrical equivalent circuit of high-voltage probe.

not suitable for avalanche operation since this is not a normal mode of operation of transistors. Matsushima *et al.*[8] have tabulated the characteristics of some of the transistors for the avalanche mode of operation. Jain *et al.*[11] have tested several other *p-n-p* and *n-p-n* transistors in the avalanche mode to determine their switching characteristics. Due to its higher breakdown voltage and easy availability we chose the *n-p-n* transistor 2N5551 for designing a high-voltage step generator. The transistor 2N5551 has a higher breakdown voltage as compared to 2N5550.[3] However, the avalanche breakdown voltages and current rating of the transistors are known to vary from piece to piece. Burn-in procedures are recommended for longer life of the stacks.[3] We did not follow these procedures. The transistors were selected by testing each transistor for avalanche breakdown voltage and rise time in the external trigger mode. The testing circuit is shown in Fig. 1.

The supply voltage was kept at 300 V and only those transistors were selected which had an output voltage 280 V or more. The fall time of the selected transistor was also not slower than 3 ns. In general, those transistors which showed a larger voltage drop also displayed a poorer fall time. During the testing stage the transistors were triggered either by the 0.3-ns rise-time calibrator pulse of the Tek 519 oscilloscope or a 0.9-ns rise-time pulse of the Tek PG-502 pulse generator. It was observed that no switching occurred for pulse amplitudes of less than 3 V. Unreliable avalanche breakdown occurred when triggered by subnanosecond rise-time pulses having a flat top of less than 3 ns in duration. With long flat-top fast rise-time pulses very reliable triggering was observed. The breakdown jitter was less than 0.5 ns limited by our system resolution. With slower rise-time pulses avalanche breakdown was highly reliable. A more detailed investigation of triggering characteristics of avalanche transistor was carried out in Ref. 11. It was a surprising observation that with fast rise-time trigger pulses a longer rise-time pulse was generated if the collector voltage was less than the self-breakdown voltage. However, no such deterioration in rise time was observed for any value of collector voltages when triggered by a 30-ns rise-time long pulse. We subsequently used an integrated output of the fast *p-i-n* photodiode to ensure reliable switching of the Marx generator.

B. High-voltage probe

A wide-band 50-Ω impedance high-voltage attenuator probe was employed for measuring the fast high-voltage pulses.[12] The electrical equivalent circuit of this probe is shown in Fig. 2. The parallel 570-Ω, 2-W resistances were mounted in a circular metal box symmetric with respect to the geometric center of the box. All the resistances were 2-W carbon composition type to ensure a sufficiently high-voltage breakdown strength and minimum inductance. A GR connector fixed on the top lid at its geometric center served as the input terminal. The output signal was obtained from the second GR connector mounted on the circular rim of the box and connected to the R-10 resistor. The output and input impedance of the attenuator was 50 Ω when the probe was coupled to a 50-Ω plug-in of an oscilloscope. The attenuation factor was 11.5×.

The attenuator was experimentally characterized by using the calibrator pulse of the Tek 519 oscilloscope. This pulse has a rise time of 0.3 ns and amplitude of 13 V across a 50-Ω load. The input and output pulses as recorded on a Tek 7834 scope are shown in Figs. 2(a) and 2(b), respectively. The attenuator rise time is at least as fast as the experimentally measured 0.75-ns instrument resolution of our oscilloscope. For better impedance matching the lower lid of the box can be rotated to slightly change the reactive circuit impedance. This can be monitored by the change in high-frequency ripple on the pulse and the depth of negative undershoot on the trailing edge of the pulse. This attenuator box has been successfully tested for input voltages up to 20 kV. With a sampling oscilloscope of 50-ps time resolution and the output of the Reed generator of the Tek 519 scope the attenuator displayed a rise time of 200 ps.

An avalanche transistor is known to have an internal resistance of a few ohms even in the avalanche mode.[3] The 50-Ω impedance of this attenuator caused circuit loading while measuring the amplitude of the output pulse generated by a stack of transistors. A Tek P-6106 probe, 300 MHz BW, and 1 MΩ impedance was sometimes used to accurately measure the pulse amplitude when operating with a single transistor. This probe can withstand only up to 500-V peak signal amplitude. Hence for high-voltage measurements of low output impedance transistor stacks the 50-Ω attenuator was modified. A series resistance of 560 Ω was connected to the input port. The attenuation factor increased to about 100×. Although the rise time of the recorded pulse changed only marginally, the imped-

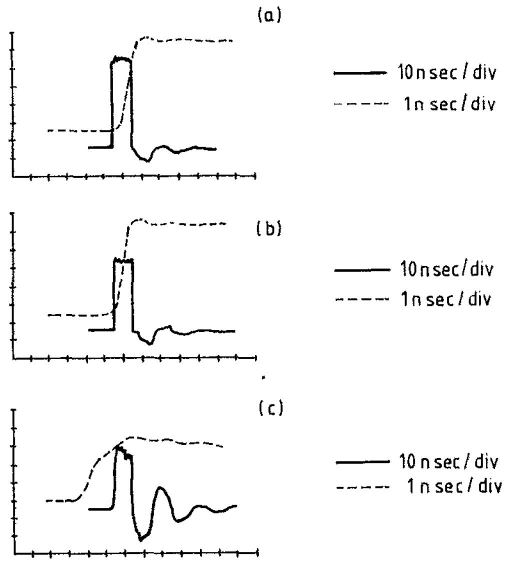

FIG. 3. (a) The TEK 519 calibrator pulse. (b) The calibrator pulse after the attenuator. (c) The calibrator pulse after the modified attenuator.

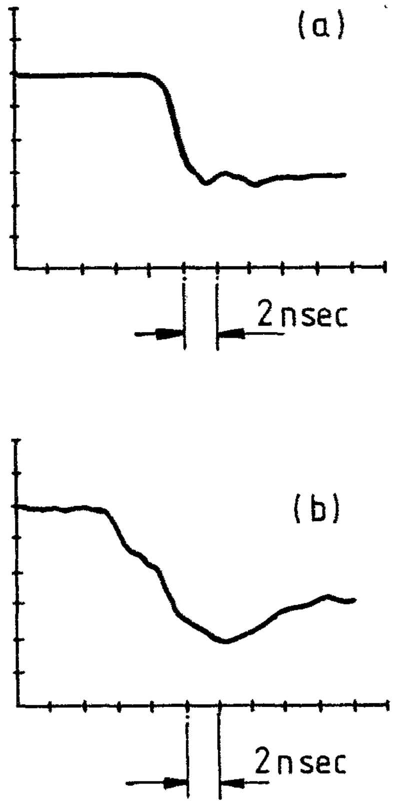

FIG. 5. Electrical step pulses generated by avalanche transistor Marx bank. (a) No load. (b) With Pockels cell as load.

ance mismatch caused a pronounced ringing. The calibrator pulse measured with this modified attenuator is also shown in Fig. 3(c).

C. Circuit

The circuit diagram of the Marx generator is shown in Fig. 4. Authors of Ref. 3 preferred 2N5550 transistors due to their greater reliability with reference to failures in case of short circuiting as compared to 2N5551 transistors. Since our design is based on 2N5551 transistors certain circuit modifications are incorporated. Three transistors were connected in series in each stage instead of one per stage. The initial trigger stages were dropped after repeated observations that neither transistor safety nor trigger jitter and output pulse rise time were affected by the absence of the pulse transformer, safety resistances, and the diodes. As a result the circuit was simplified. The circuit failure is negligible and transistor failures were detected only a few times over 1-y continuous operation of this circuit. In contrast, with a single transistor in each stage, even during the testing stage of the circuit continuous transistor failures were observed. In the laser setup the circuit is triggered by the integrated output of a *p-i-n* photodiode. The *RC* time constant is determined by $R = 580$ kΩ and $C = 5$ nF. For more reliable triggering and isolation of *p-i-n* photodiodes a transistor stage based on 2N91876 was added after the integrator. The slow rise-time pulse triggered the first stage of the Marx generator. A jitter of ±1 ns is recorded in the generation of the high-voltage step pulse when triggered by the integrated signal. In about 10% of the shots a very large jitter of up to ±2.5 ns is observed, resulting in large output pulse energy fluctuation in 10% of the shots.

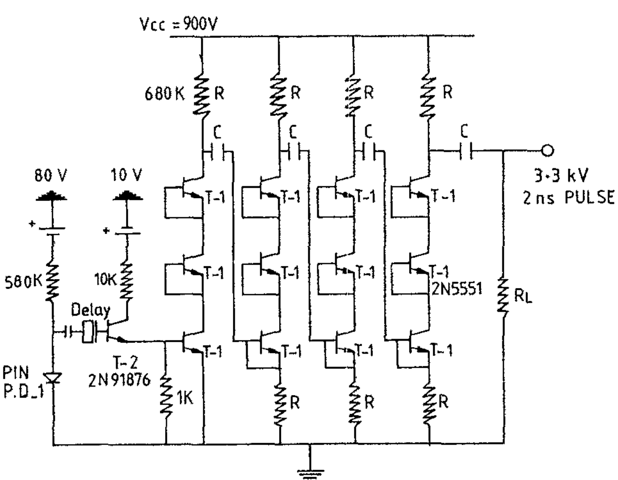

FIG. 4. Circuit diagram of avalanche transistor Marx generator.

A negative fast pulse is generated at the output of the Marx generator [Fig. 5(a)]. The supply voltage is 900 V. From four stages we obtain a ~3.3 kV step pulse of 1.5 ns fall time for an open-ended circuit. This is slightly faster than that reported in Ref. 10 for 2.4-kV pulses. The charging rise time is determined by the *RC* time constant of the resistance R_2 ($R_2 = 680$ kΩ) and the capacitance C_2 ($C_2 = 200$ pF). The C_2 were low-inductance ceramic capacitors. Since the repetition rate of our laser is only 0.1 Hz the charging rise time was not critical. The avalanche breakdown delay was measured at different stages. The first

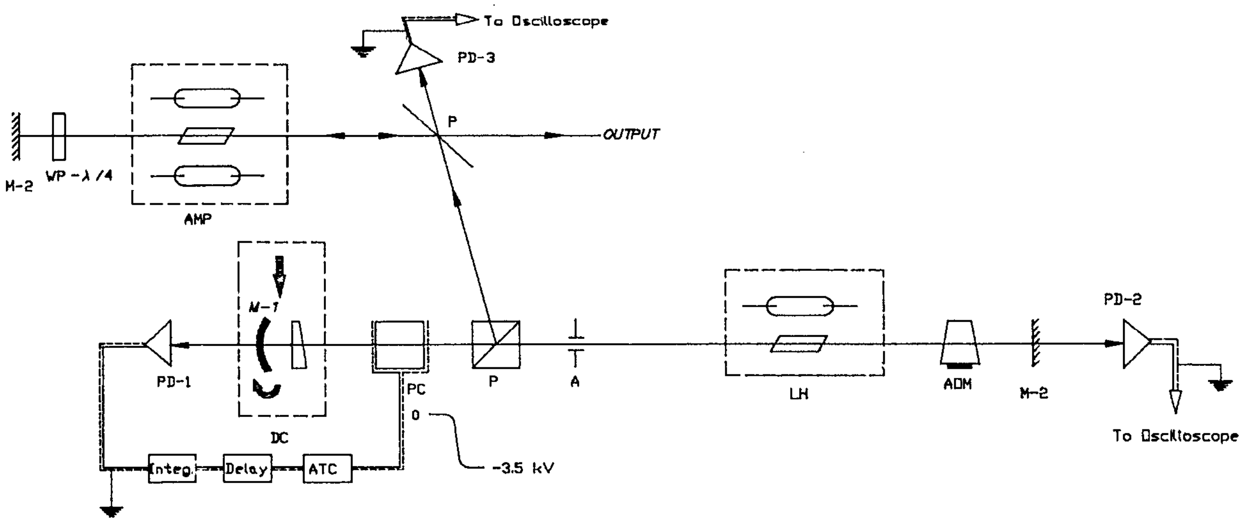

FIG. 6. Active-passive mode-locked cavity dumped glass laser with amplifier. dc-flowing dye cell with mirror, *M*1 ($R = 100\%$); PC—Pockels cell; *P*—polarizer; *A*—aperture; *M*2—100% reflectivity plane mirror; LH—Laser head with flash lamps; PD-2, PD-3—biplanar photodiodes; PD-1—*p-i-n* photodiode; ATC—avalanche transistor circuit; AOM—acousto-optic modulator; AMP—amplifier; WP—$\lambda/4$, quarter-wave plate.

stage delay was 8–9 ns while the total circuit delay was approximately 10 ns. This delay is a little shorter than that reported in Ref. 10.

This voltage step generator was used to drive an INRAD model 212-150 Pockels cell. The intrinsic 11-pF capacitance of the Pockels cell caused a deterioration in fall time to 4.0 ns [Fig. 5(b)]. The 50-Ω impedance matched INRAD model 252-290 Pockels cell had a higher capacitance of 30 pF. This larger capacitance led to a longer fall time of the high-voltage step pulse and hence the previous model was preferred.

III. LASER SETUP AND OPTICAL PERFORMANCE

The schematic setup of active-passive mode-locked Nd:phosphate glass laser is shown on Fig. 6. The high-voltage pulse generator with the integrator is mounted on a breadboard. The unit is kept very close to the Pockels cell and is connected to it by a 2-cm-long wire. Even a small length of coaxial cable considerably degraded the performance of the circuit both in terms of fall time and peak amplitude. The optical schematics of the cavity dumper is based on the standard technique of rotation of polarization when a $V_{\lambda/4}$ voltage is applied to the Pockels cell. Initially the Pockels cell is at zero-bias voltage. The high Q state of the resonator favors the buildup of intracavity radiation. At a preset level which can be controlled by neutral density filters the avalanche transistors are triggered. The trigger level is approximately 4 V. After an intrinsic delay of 10 ns and additional cable delays a 3.3-kV negative step pulse is applied to the Pockels cell. The polarization of the circulating optical radiation is rotated by π in double pass through the Pockels cell and is rejected out by the polarizer *P*. This rejected radiation is the useful output of the laser.

In order to test the optical switchout characteristics of the cavity dumper the laser was initially operated in the free-running mode. The avalanche transistor circuit was triggered by the first free-running spike. Figure 7 displays (a) the first spike, in the off state of the cavity dumper, (b) the spike terminated due to the firing of the cavity dumper

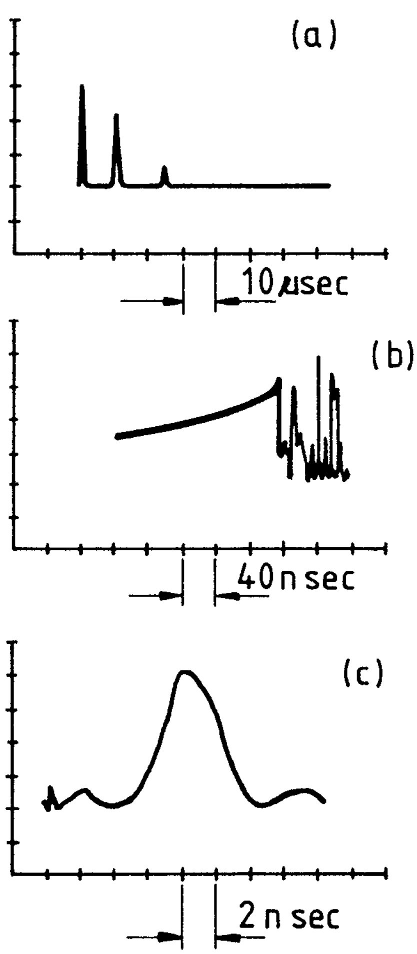

FIG. 7. (a) The free-running spike. (b) The spike terminated by the firing of the cavity dumper. (c) The cavity dumped output pulse.

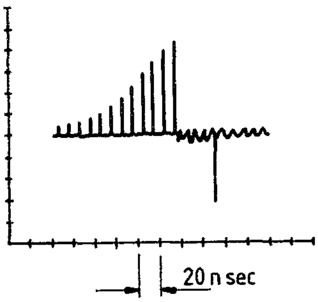

FIG. 8. Mode-locked pulse train and the single switched-out pulse (inverted).

as detected by PD2, and (c) the simultaneously recorded output pulse by detector PD3. The fall time of the terminated spike was 3 ns (0%–100%). The output pulse FWHM was 4 ns. Both PD-2 and PD-3 were Hamamatsu biplanar photodiodes with rise times of 100 ps or less. Better than 85% switching efficiency is estimated from the oscilloscope signals.

In the mode-locked regime in the high Q condition of the cavity a single mode-locked pulse is formed due to the combined action of active and passive modulators. The Kodak 9860 dye dissolved in 1,2 dichloroethane is the passive mode locker. A Quantronix model 302 acousto-optic mode locker actively modulates the losses) in the cavity. The round-trip time of the resonator was 10 ns. However, the maximum available switching time as determined by the sum total of 0%–100% fall time of the step pulse and its jitter is slightly less due to the physical separation between the Pockels cell and mirror $M1$. An optical pulse originating at a Pockels cell and travelling towards mirror $M2$ will return to the Pockels cell in a time ~8 ns. The full $v_{\lambda/4}$ voltage must be applied within this time. The switching time of 4–±1 ns of the cavity dumper circuit fully satisfied this condition and hence reliable and complete pulse switchout with an efficiency close to 1 is obtained. Figures 8(a) and 8(b) show the mode-locked pulse train as detected by PD2 and the simultaneously recorded switched-out single pulse as detected by PD3. The pulse duration measured by two-photon flourescence was 6 ps.

The laser is operated at low dye concentrations due to the risk of damage to intracavity optical components. The lowest damage thresholds were determined by the Glan polarizer. Output pulse energies were restricted to 0.5 mJ by the selected dye concentrations. We estimate better than 85% switching efficiency from the initial tests carried out in the free-running mode. The intracavity power is estimated to be ~3.0 GW/cm^2. The guaranteed damage threshold of the Glan polarizer for 10-ns pulses is 300 MW/cm^2. For picosecond pulses an order-of-magnitude higher damage threshold is expected.

The contrast ratio between the peak amplitude of the leakage pulse train and the amplitude of the switched-out pulse was measured after a double pass through the amplifier and the second thin-film polarizer. The contrast was better than 10^3 both in the case of amplification and without amplification of the signal. The full-angle beam divergence measured by a Vidicon camera and a line selector unit[13] was about 0.6 mrad.

IV. DISCUSSION

In conclusion, we have built an all-solid-state cavity dumper for mode-locked laser. The optical switching times are 2 ns (10%–90%). The electrical high-voltage pulse generator based on an avalanche transistor has demonstrated a very reliable performance over a period of 1 year. The same circuit was tested for the generation of step voltage pulses of up to 5 kV with 1.5 ns fall time. However, the data on long-term reliability at these voltages is not available at present. The Marx bank generator described here is also suitable for the more conventional Q-switched operation of glass lasers. There are certain advantages over the conventional Blumlein circuits such as the absence of continuously applied dc voltage on the Pockels cell and the use of lower supply voltage. A small disadvantage is the requirement of an additional $\lambda/4$ waveplate inside the cavity.

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