Laser pulser for a time-of-flight laser radar

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A laser pulser for a pulsed time-of-flight laser radar is presented. The pulser is constructed using a single avalanche transistor in order to keep the schematic simple and to avoid the problems encountered when connecting several avalanche transistors in parallel. The schematic of the laser pulser was optimized and it was noticed that the optical peak pulse power of the laser can be increased significantly by adding a parallel capacitor to the laser. The measured increase of the optical power was up to 26%. The simulations show that the parallel capacitor and also the serial inductances of the components in the laser pulser play a significant role in adjusting the shape of the current pulse. In order to find the transistor, which gives the highest current, the properties of several transistor types were compared. It was noticed that there can be a great difference between the avalanche properties of a group of transistors even if they are of the same type. © *1997 American Institute of Physics.* [S0034-6748(97)00906-4]

I. INTRODUCTION

A semiconductor laser is a handy component compared to other solid-state lasers in pulsed time-of-flight (TOF) laser radars, because it is small, mechanically stable, relatively cheap, and has good efficiency. Both single heterostructure (SH) and double heterostructure (DH) lasers are suitable for use in laser transmitters. The optical peak pulse power of some laser types may exceed 100 W.

In TOF laser radars, short, powerful optical pulses are needed. The resolution value of distance measurement is determined by the ratio between noise value and slew rate of the measurement signal. The resolution value may be improved by decreasing the rise and fall times or increasing the output power of the transmitted pulse or decreasing the total noise value of the measurement pulse and receiver channel electronics. Here it is assumed that the time-pickoff circuit is based on utilizing both the leading and trailing edges of the pulse. In practice, a receiver channel with a bandwidth of 100 MHz is possible to fabricate using commercially available components,[1] and a suitable width for laser pulses is in the range of 5–10 ns. The amplitudes of the current pulses needed for lasers used in TOF laser radars are to the order of a few tens of amperes. When the pulses are short, only a few nanoseconds in length, it is possible to increase the output pulse power by driving the lasers with significantly larger currents than the nominal current. For this reason, pulse currents even as high as 100 A can be used.

The pulser electronics usually consists of a capacitor and a switch, which discharges the charge of the capacitor to the laser. The capacitor is charged again during the time between the two sequential pulses, and a new pulse is ready to be sent. The switch may be, for example, an avalanche transistor, a thyristor, or a metal-oxide-semiconductor field-effect transistor (MOSFET). Usually an avalanche transistor produces the fastest current pulses. The disadvantage of MOSFETs is their high gate capacitances and the normal silicon thyristors are not fast enough for laser pulsers. However, with GaAs thyristors, a rise time of less than 500 ps at the current of 100 A has been achieved, but the GaAs thyristor is yet under development.[2]

Semiconductor lasers can be very different as comes to the shape of the current pulses and optical output pulses. According to the rate equations which describe the dynamic operation of a laser, the shape of the optical pulse in time scale does not follow linearly the shape of the current pulse, and because of gain switching phenomena, the rise time of an optical pulse can be much shorter than the rise time of the current pulse.[3]

The aim of this work was to construct a laser pulser which can produce as large pulse currents as possible with a single avalanche transistor. For this purpose, three normal switching transistors and a specially manufactured avalanche transistor from Zetex Co. are compared when used as a switch in a laser pulser. The switching transistors were selected from a larger group of transistor types used in earlier experiments. The operation of the avalanche pulser including its parasitics is studied in detail and the possibilities to optimize its performance are discussed.

II. THE STRUCTURE OF A LASER PULSER

A. The basic schematic diagram

In Fig. 1, a schematic diagram of a basic avalanche transistor laser pulser is presented. The lead inductances have been taken into account in the components which carry high current. The energy used in one current pulse is charged through the resistors R3 and R4 in the capacitor C2. A typical value for R3 is tens of kilo-Ω (for a repetition frequency of less than 10 kHz) and for R4, for example, 100 Ω. In the position of R4, also a diode in opposite direction to the laser can be used. The value of R4 must not be allowed to rise too high, or else the voltage across it during the charging cycle may exceed the maximum reverse voltage of the laser. The avalanche transistor operates as a switch which moves to on-state after the triggering pulse has been applied to the base of the transistor. The capacitor is discharged mainly through the laser because the laser is a low ohmic load in

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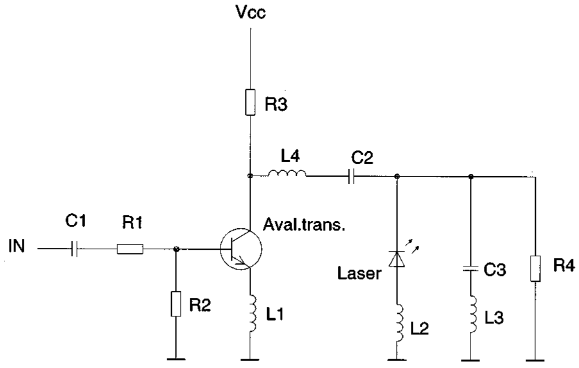

FIG. 1. The schematic diagram of an avalanche pulser.

forward direction. A current measurement or a limiting resistor may be connected in series with the laser. By changing the value of C3, the shape and amplitude of the current pulse through the laser can be adjusted, because when C2 is discharged, part of its energy is stored in C3 and that energy is discharged through the laser in a period which is determined by the values of the (L2+L3) C3 oscillation circuit.

The values of the components are adjusted so that the needed amplitude, width, and repetition frequency of the current pulse are achieved. The value of R3 is adjusted according to the repetition frequency so that the voltage of C2 is able to increase to a level high enough for avalanche operation. If the value of R3 is decreased too much, the avalanche transistor may stay permanently in on-state, making the temperature rise too high and so destroy the transistor.

A simple approximation for the value of C2 is obtained from the equation:

$$\mathrm{C2}\times\Delta U=I_p\times\Delta t. \tag{1}$$

Increasing the value of the capacitor C2 increases both the width of the current pulse Δt and the peak amplitude of the current I_p. By increasing the operating voltage, the amplitude of the current pulse increases, and in practice, at the same time, the width of the current pulse decreases slightly, because the on-state resistance of the transistor decreases.

The highest operating frequency of the avalanche pulser is limited by the temperature of the transistor and the charging speed of the capacitor. The avalanche transistor must cool enough between the two pulses so that the temperature would not increase cumulatively and lead into a secondary breakdown. The cooling rate is defined by the dimensions of the active area of the transistor. The larger the transistor, the smaller the largest possible operating frequency. If the power switched by the avalanche transistor is small enough, even a frequency in the range of hundreds of MHz is possible.[4]

The capacitor discharged may also be an open-ended delay line with a characteristic impedance Z_0. When the impedance of the delay line is matched to the impedances of the circuit (defined mainly by R_L), a close approximation of a square pulse may be obtained on the resistor R_L. The delay line may be realized with a coaxial cable or a microstrip line[5] or with a network of capacitors and inductances.[6]

Several transistors may be connected in parallel in order to increase the peak current amplitude through the laser. However, as the temperature changes, the synchronization of the transistors may be difficult. For this reason, it is important to reach high current amplitudes with a single transistor.

B. The operation of an avalanche transistor

Plenty of articles and theoretical models of avalanche operation have been published during the past years.[7–11] Avalanche transistors have been used for pulsing semiconductor laser from the beginning of the 1960s.[12–15]

A simplified description of the operation of an avalanche pulser can be described as follows: When a NPN transistor in an avalanche pulser is in off-state, a large reverse voltage is applied between the collector and base. Then the depletion region between the collector and the base extends deep into the base and the remaining effective width of the base is small. Avalanche operation can be started by bringing a current pulse to the base, and then a large amount of electrons is injected from the emitter to the base (in NPN transistor). The electrons are swept rapidly from the base to the collector where the breakdown is started. In the breakdown, the minority carriers in strongly reverse biased collector-base region gain sufficient energy to generate new hole-electron pairs by impact ionization, and, as a consequence of the cumulative process, a strong current pulse flows between the collector and the emitter.

When an avalanche transistor is used as a switch, as shown in Fig. 1, a leakage current MI_{CBO} flows from the collector to the base in the off-state, where M is the avalanche multiplication of the leakage current between the collector and the base. If there is a resistor R2 between the base and ground, a current MI_{CBO} flows through it in bias condition, and the bigger the value of the resistor, the easier it is for the base-emitter junction to transfer to on-state, thus causing a breakdown between the collector and the emitter. The largest possible bias voltage between the collector and the base BV_{CBA} may be adjusted close to BV_{CBO} (the largest breakdown voltage between the collector and the base when the emitter is open), if the base-emitter region is reverse biased through some low-ohmic impedance (Fig. 2).

When the transistor is switched to on-state, the operating point moves rapidly from point A to B in the load line, in Fig. 2. During the breakdown, a voltage $\sim BV_{\mathrm{CEO}}$ (a breakdown voltage between the collector and the emitter with an open base) can be detected between the collector and the emitter. The voltage difference $BV_{\mathrm{CBA}}-BV_{\mathrm{CEO}}$ remains across the load, which is the resistor RL in the ideal case and the maximum pulse current I will be

$$I=\frac{BV_{\mathrm{CBA}}-BV_{\mathrm{CEO}}}{R_L}. \tag{2}$$

In a case where the values of the series inductances would be negligible, the pulse current would have very short rise time and slower, exponential trailing edge of the pulse. However, in practice, the series inductances limit the maximum pulse current and they also shape the form of the pulse more symmetrical, closer to a shape of a Gaussian curve.

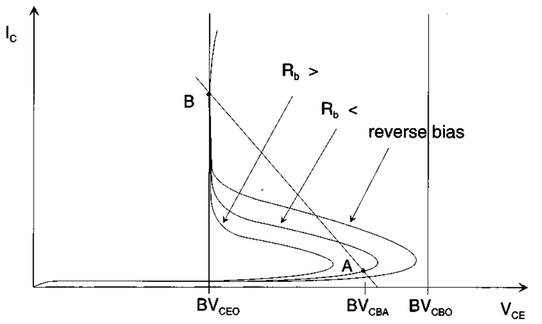

FIG. 2. The characteristic curves of a bipolar transistor in the avalanche region in three cases: with a negative base-emitter voltage and with a small and a large resistor between base and emitter.

If the value of the resistor R2 is increased, the bias voltage BV_{CBA} must be decreased accordingly and so results in a smaller current pulse to the load. The reason why the voltage BV_{CEO} is remarkably smaller than BV_{CBO}, is that when the avalanche breakdown is started and the current is flowing from the collector to the emitter, the electrons are supplied from the emitter to the base and almost all of them are swept to the collector and they may take part in the avalanche multiplication process. For this reason, the avalanche multiplication factor M and the voltage BV_{CEO} needed to hold the avalanche process are smaller than in the case of avalanche breakdown between collector and base with open emitter (BV_{CBO}), in which case no electrons come from the emitter.[16] The voltage V_{CEO} can be calculated as

$$V_{\mathrm{CEO}}=\frac{V_{\mathrm{CBO}}}{\sqrt[n]{\beta}}, \tag{3}$$

where n varies between 3 and 6 depending on the V_{CBO} and base resistivity[17] and β is the common-emitter current gain. In practice, the voltage BV_{CEO} depends on the amount of current. In Ref. 9, it has been measured that with the transistor 2N2218A the voltage BV_{CEO} will be higher with low and high currents and that it reaches the smallest value between them.

However, there are also other effects which may take place at high currents. At large current amplitudes, the electric field distribution in the collector region is reconstructed and it may affect to the on-state voltage BV_{CEO}.[18] This has not been taken into account in the calculation above.

III. COMPARISON OF SOME AVALANCHE TRANSISTORS

Several commercial bipolar power transistor types were compared in order to clarify, how well they were suited for avalanche operation. These types were selected from a larger group of transistors used in previous experiments. In comparison, the Zetex ZTX415 packaged in a SOT-23 case was used as reference type. The other types compared were MJE200 and 2N5190 from one manufacturer and 2N5192 from two manufacturers, all packaged in TO-225AA case.

The operating voltage of ZTX415 was limited to the maximum voltage recommended by the manufacturer. The maximum voltages of other transistors were tested with a curve tracer and they were limited in avalanche operation to approx. 10–20 V below BV_{CBO}. The reliability of the transistors in avalanche operation, however, was not tested. Zetex provides transistor lifetime charts as a function of supply voltage. However, also the other types tested in this work have been reliable in laser pulsers and they have been tested in laboratory as well as in real industrial environment for at least some hundreds of hours with no transistors being destroyed.

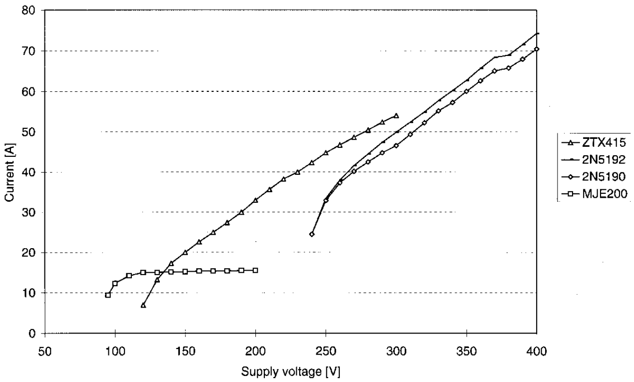

FIG. 3. The peak amplitudes of current pulses as a function of supply voltage with different transistors, $\mathrm{R}_L=1$ ohm, C2=1 nF.

The circuit used in the measurements was a normal avalanche pulser circuit with a resistive load. The measurement bandwidth was 1 GHz. The value of the capacitor discharged was 1 nF and the load resistance was 1 Ω (three 3.3 Ω surface mount resistors in parallel). The use of surface mount components helps to keep the lead inductances at minimum and the current measurements more reliable.

A. The current pulses with a resistive load

When the supply voltage was increased from the minimum to the maximum (Fig. 3), the peak currents increased almost linearly and the widths of the pulses were decreased by ~7% to 8%, excluding the range of very low operating voltages, where the shape of the pulse changed markedly with small changes in the supply voltage. The full width at half-maximum (FWHM) was ~7 ns with 2N5190/5192 and MJE200 transistors and ~6 ns with ZTX415 transistor.

However, with MJE200, an increase in the supply voltage did not rise the current amplitude after supply voltage of 130 V. The ZTX415 operates at a large range of currents, approx. 10–55 A, when the highest value of the supply voltage is limited to 260 V by the recommendation of the manufacturer. The transistors 2N5190 and 2N5192 give roughly the same peak current amplitudes, 30–75 A, in a voltage range of 250–400 V.

The rise times were clearly shorter with transistors MJE200 and ZTX415 (~2.6 ns) than with types 2N5190 and 2N5192 (~3.7 ns) in the range of a normal avalanche operation. The dependence of the rise time on the supply voltage was low, less than 10%. At least with the Zetex transistor, the shorter rise time can be explained with smaller lead inductances than in TO-225AA packaged types. The fall times varied in the range of 3.5–5 ns.

In Fig. 4, the pulse current measured as a voltage pulse

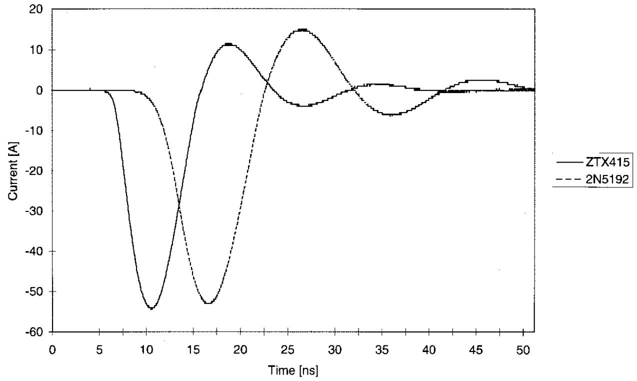

FIG. 4. The measured current pulses from ZTX415 ($Vcc=260$ V) and 2N5192 transistors ($Vcc=300$ V).

across the 1 Ω load versus time of transistors ZTX415 and 2N5192 have been presented. The supply voltages of ZTX415 and 2N5192 were 260 and 300 V, respectively. The beginning of the time axis in Fig. 4 is adjusted to the beginning of the trigger pulse at the base of the transistor. From the oscillation frequencies of the "tails" of the current pulses, it was possible to calculate the sum values of the inductances in the circuit: $L_{\text{tot}}=5.5–9.1$ nH. Calculating the inductances of the printed circuit board and taking into account the data sheet values for the inductances of the transistor cases gave results of $L_{\text{tot}}=7–11.5$ nH. The difference between the measurement and the calculation may result from an error in the estimation of the capacitor value or the nonlinearity of the on-state resistance of the avalanche transistor or discharging of the charge of the p-n junctions of the transistor, when the transistor is switched to off-state.

The measured on-state voltages and resistances of the avalanche transistors at the peaks of the current pulses are presented in Fig. 5. It can be seen that the on-state resistances decrease when the current increases.

The amplitude and delay of the current pulse of transistors ZTX415 and 2N5192 as a function of the amplitude of the trigger pulse are presented in Fig. 6. The FWHM of the trigger pulse taken from a 50 Ω pulse generator was 50 ns and rise and fall times were both 1 ns. The supply voltages were 260 and 300 V for ZTX415 and 2N5192, respectively. From Fig. 6. it can be concluded that the possible individual differences in the delay times of the current pulses can be compensated by adjusting the amplitudes of the trigger pulses individually, for example, in the case where several transistors are connected in parallel.

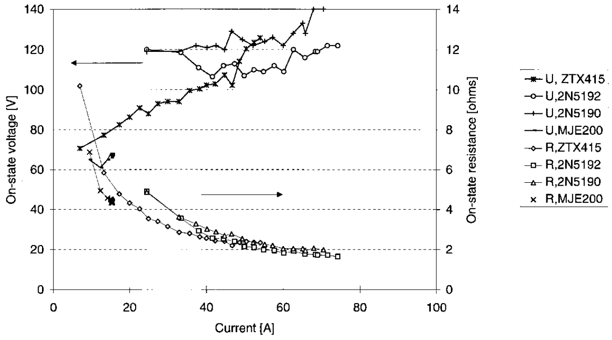

FIG. 5. The on-state voltages and resistances of different transistors in avalanche operation.

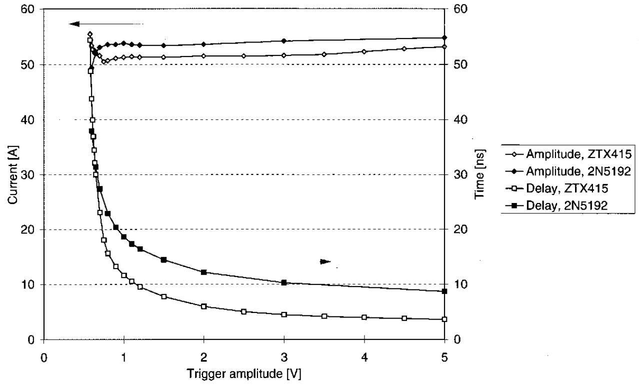

FIG. 6. The delay and amplitude of the load current pulse vs the amplitude of the trigger pulse.

B. The shapes of optical pulses from lasers

The optical pulses from two pigtailed lasers, LD65 and CVD197 (manufacturer Laser Diode Inc.), were measured with a combination of a digital sampling oscilloscope and a fast InGaAs photodiode connected to a 50 ohm input of the oscilloscope. It was estimated that the upper bandwidth limit of the measuring system was more than 10 GHz, even taking into account the mode dispersion of the multimode fibers used in the lasers as well as the jitter between the trigger and light pulses of the pulser.

The light output versus time of lasers LD65 and CVD197 are presented in Fig. 7. The pulser transistor was ZTX415. The light pulse from LD65 is presented on the full bandwidth of the measuring system and also (filtered digitally in the oscilloscope) on normal laser radar bandwidth, 100 MHz.[1] With both lasers, the rise time of the leading edge of the light pulse is less than 100 ps and with LD65 the amplitude of the fast pulse is remarkably larger than the amplitude of the slower part of the light pulse. It is very prob-

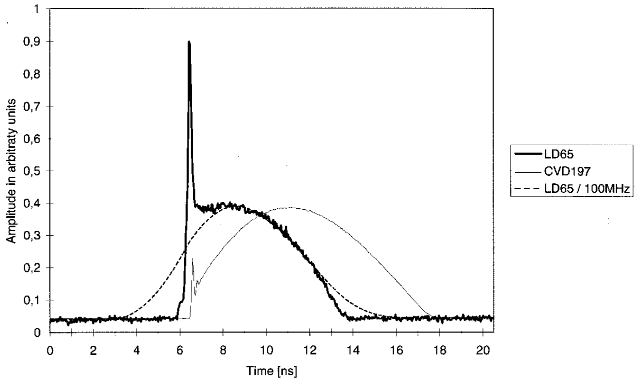

FIG. 7. The optical pulses from lasers LD65 and CVD197 with full bandwidth of the system and from LD65 with 100 MHz bandwidth. The delays are not comparable to each other.

TABLE I. Measurement results of current and optical pulses from a circuit, in which a capacitor has been used in parallel with laser CVD197.

	Current of series resistor			Optical pulse	
Capacitance	I_{peak} [A]	t_{rise} [ns]	t_{width} [ns]	t_{width} [ns]	P_{peak} [W]
0 pF	29.6	3.8	9.2	8.9	57
100 pF	30.9	5.5	9.0	8.7	58
200 pF	26.5	2.7	10.5	7.2	72
300 pF	26.7	2.4	12.4	7.2	72
400 pF	28.3	2.5	13.8	7.5	70

able that the fast part of the light pulse is due to normal gain switching phenomena in semiconductor lasers.[2]

The maximum peak power output from the laser LD65 was measured with two transistors, ZTX415 and 2N5192. The rated optical power at 40 A current in room temperature is typically 10 W for LD65. With the maximum operating voltages of ZTX415 and 2N5192 (300 and 400 V), the maximum optical power was 20.0 and 21.3 W, respectively.

The FWHM and peak power of the optical pulses from CVD197 as a function of the value of the parallel capacitor C2 are presented in Table I. The measurement bandwidth was approx. 600 MHz. The avalanche transistor was ZTX415 and the supply voltage 230 V. It can be noted that when a capacitor in the range of 100–400 pF is connected in parallel with the laser, the peak power of the optical pulse can be increased. In this case, the maximum amount of increase was 26%. The width of the optical pulse decreases, because the total amount of energy stored in capacitor C2 is the same in all cases. Now the measured current through the series resistor does not show the right value of current flowing through the laser, which can be seen more clearly by SPICE simulation.

C. The comparison of 2N5192 transistors manufactured by different companies

In Fig. 8, a comparison table of 2N5192 transistors manufactured by two different companies is presented. The transistors were classified according to the maximum peak amplitude of the current pulse of the load resistor. Approximately 20 transistors from both manufacturers were measured. The supply voltage was 300 V except in the cases when the V_{CBO} voltage was so low that the supply voltage had to be decreased for that reason. Especially with transistors made by company n:o 2 the highest supply voltage possible was in the range of 200–250 V. The load resistance was 3 Ω and capacitance of the capacitor discharged was 1.6 nF.

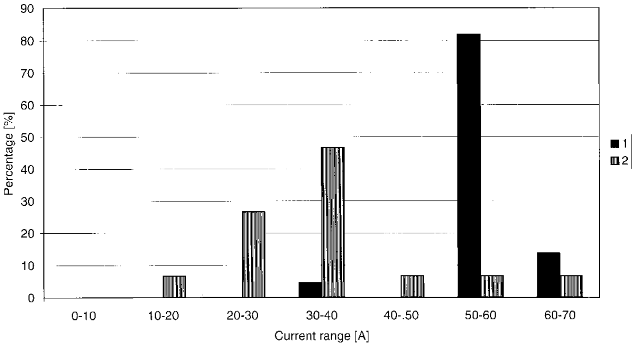

FIG. 8. A comparison of maximum peak current amplitudes achieved with 20 items of 2N5192 transistors manufactured by two different companies.

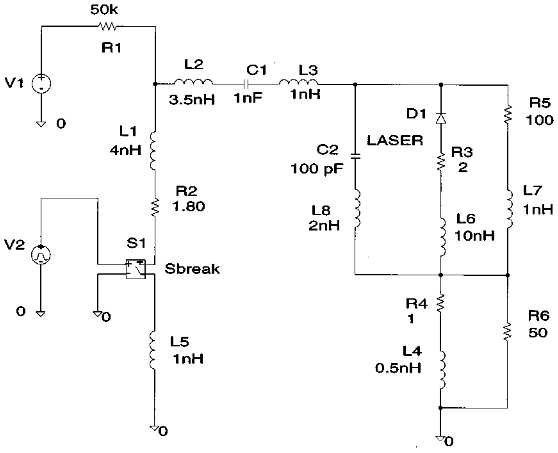

FIG. 9. The SPICE model for an avalanche pulser with the laser and the parallel capacitor of the laser.

From Fig. 8, it can be seen that with the transistors made by company n:o 1 the individual differences are much smaller and they clearly give higher peak current amplitudes than transistors made by company n:o 2. The differences are possible to explain with the individual differences in the common-emitter current gain β and in the breakdown voltage V_{CBO} of different transistors. The measured current gains ($I_b = 10\ \mu$A) were in the ranges of 47–54 and 25–114 with the transistors made by the companies 1 and 2, respectively. The breakdown voltages V_{CBO} were in the ranges of 395–420 and 120–400 V with the transistors made by the companies 1 and 2, respectively. From the measurements presented above, it can be concluded that normal bipolar transistors should always be tested individually when used in avalanche operation. Testing of β and V_{CBO} gives a first order prediction of the performance of the transistor in the avalanche pulser.

IV. THE SPICE MODEL OF AN AVALANCHE PULSER

The effect of using a parallel capacitor with the laser on the shape of the current pulse was studied using a simulator. A simulating program with integrated circuit emphasis (SPICE) model of an avalanche laser pulser is presented in Fig. 9. The avalanche transistor is modeled as a series connection of a resistor R2, inductor L1, and an ideal switch (S1), which has an off-state series resistance of 10 MΩ and on-state resistance of 10 MΩ. The inductances L2 and L3 are the inductances of the printed circuit board and capacitor C1, respectively. The inductance L1 is the inductance of SOT23 or TO-225AA case (1 or 4 nH, respectively). The laser was modeled as a connection of diode D1, resistor R3, and inductance L6. The resistance of R3 is the internal series re-

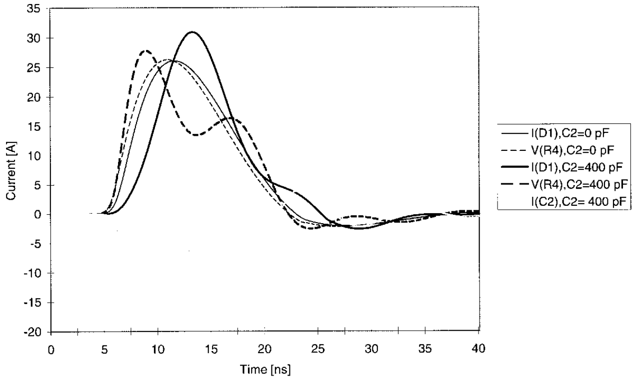

FIG. 10. The simulated shapes of current pulses through the laser and voltage pulses across the series resistor with C2=0 pF (thin lines) and C2=400 pF (thick lines) and current through the capacitor C2.

sistance of the laser (2 Ω for CVD197). The internal model of D1 has a diode capacitance of ~100 pF and a breakdown voltage of 10 V.

The effect of adding a parallel capacitance C2 with the laser can be seen in Fig. 10. The current pulse through the laser is sharper and has approx. 20% larger amplitude, when C2 is increased from 0 to 400 pF. When C2 is as large as 400 pF, there is a great difference between the pulse shapes of the current going through the laser and the voltage pulse measured across the series resistor. The shape of the current pulse can be measured reliably only, if it is measured as a voltage pulse across the series resistor, when the value of the parallel capacitor C2 is 0 pF. In all cases, a reliable estimation of the value of the current going through the laser can be obtained by measuring the optical peak power.

The current pulses going through the laser D1 and the parallel capacitor C2 show that C2 stores the energy for a while and releases it through the laser in the ideal situation at a moment which coincides with the peak of the main current flowing through the laser from C1.

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