LASER-DIODE BASED PHOTOACOUSTIC SIGNAL EXCITATION FOR BIOMEDICAL APPLICATIONS

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Abstract

Recently, powerful pulsed laser diodes have attracted significant attention as a suitable means for the excitation of photoacoustic signals. Efficiently driving the laser diodes is the key to optimal photoacoustic signal generation. In this paper we propose a laser-diode based photoacoustic signal excitation system that relies on the peculiar phenomena of current mode second breakdown (commonly referred to as avalanche mode) intrinsic to bipolar junction transistors.

Starting from a single transistor driver capable of switching up to a few hundred mA in 30ns, we increase the switching capability by first stacking several transistors in a Marks-Bank design and considering a custom sandwich-like topology, which can hold up to eight identical single transistor drivers that are vertically stacked along the edge of a horizontal circular base, which holds the laser diode.

1. INTRODUCTION

The photoacoustic imaging (PAI) technique is swiftly maturing and is expected soon to be implemented in the clinical practice [1]. Usually Q-switched Nd:YAG pumped OPO, dye or Ti Sapphire laser systems are used for the efficient photoacoustic signal generation. However, they operate at low pulse repetition frequencies (PRF), may require cooling and have large dimensions, all of which is limiting their practical application in the clinical environment [2].

Powerful pulsed laser diodes (PLDs) provide only a few μJ of output energy [3], but can operate at much higher PRFs and have small dimension, which turns them into an attractive alternative to the more powerful, but bulky systems.

PLDs require tens of amperes of forward current crammed in a few hundred nanoseconds with short rise/fall times in order to generate an optimal photon flux [4]. To achieve this, different strategies can be applied, among which are the use of high–power field effect transistors, high–speed silicon controlled rectifiers, step recovery diodes and others [5]. An interesting alternative to these is the use of avalanche mode (current mode second breakdown) transistors, which besides being relatively cheap offer somewhat easily adjustable, variable length and amplitude output signals. Moreover, by using a Marks-bank configuration very high current switching can be achieved. In order to meet the stress confinement rule, intrinsic to the efficient photoacoustic signal generation [6], all transistors must breakdown simultaneously. To achieve this goal a sandwich topology is proposed, which guarantees that the signal paths from the transistor emitters to the laser diode will have the same length and thus induce the same delay.

2. THE SINGLE TRANSISTOR DRIVER

The basic laser diode driver block is depicted in Figure 1. It consists of a differentiator input circuit (C_1-R_1), an energy storage element (capacitor C_2) and a few resistors limiting the currents and setting the transistor in the desired mode.

2.1. Circuit design

To enter breakdown, large supply voltage must be applied between the transistor's reverse biased collector-base p-n junction. This increases the energy of the free charge carriers diffusing through the junction, with some gaining enough energy to release a new electron-hole pair upon collision with atoms from the crystal lattice. Typically this happens around BV_{CBO}, where the current flowing through the collector p-n junction increases above a threshold value after which the avalanche process can sustain itself. By adding the energy storage capacitor C_2 and keeping resistance R_4 small the current through the collector junction is kept large enough for avalanche breakdown to occur [7]. The avalanche process duration can be roughly defined as $\tau_d = C_2(R_4 + R_{LD1})$ and will seize once the current through the collector junction drops below the threshold level.

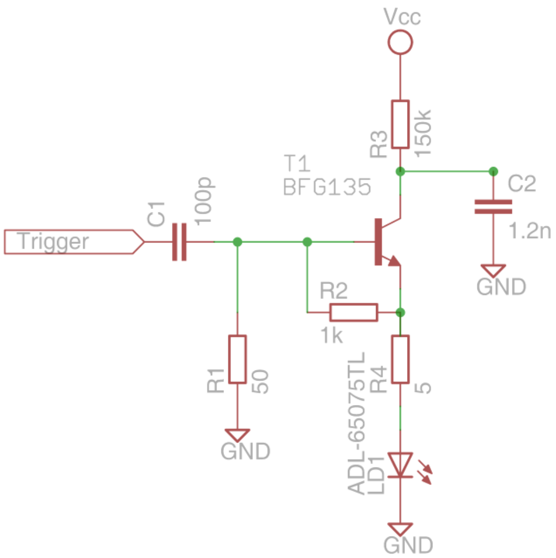

Figure 1. The laser driver circuit using BFG135 in avalanche mode and exciting a laser diode

The signal amplitude depends on the characteristics of capacitor C_2, the supply voltage V_{cc} and resistance R_4. Increasing V_{cc} has a limited effect on the current flowing through LD_1, while increasing C_2 and decreasing R_4 modifies tremendously the signal amplitude and duration. Basically, smaller capacitance leads to smaller amplitude, but fast rise/fall times of the output signal, while smaller R_4 increases the current flowing through the laser diode. Finding the balance between the two requires some empirical work the result of which is the circuit depicted in Figure 1.

Another major pillar in the design is the choice of the transistor. Special avalanche transistors are available (such as ZETEX's ZTX415 [8]), but it is well known that almost any NPN bipolar junction transistor can be used in avalanche mode [9]. In the current design NXP's BFG135 is implemented, which besides being wideband benefits from low BV_{CBO}. Actually, stable breakdown occurs at V_{cc} = 40V, which facilitates the design of the circuit and imposes significantly lower power supply requirements than those needed by 2N2369, ZTX415 and other.

2.2. Experimental results

Avalanche breakdown takes place when 5V, 200ns square pulses are applied to the base of BFG135 with a PRF of 1 kHz. The typical output (taken from R_4) and collector voltage are depicted in Figure 2.

The collector voltage reveals the process of charge and discharge of the energy storage capacitor C_2. Initially, it is fully charged through resistor R_3 and when the base-emitter junction forward biases, it discharges through the transistor driving the laser diode. The process is very fast with rise time in the order of 6ns and total duration of the semi-Gaussian part of the signal of approximately 30ns.

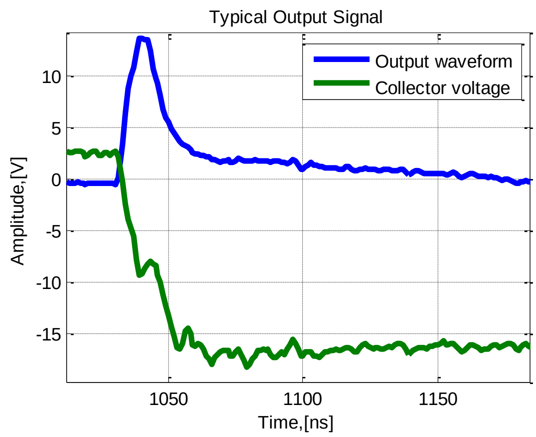

Figure 2. Emitter (top) and collector voltage (bottom) for the driver solution of Figure 1

However, the rear edge is typically less steep than its leading counterpart and contains a slowly decaying part that stretches for hundreds of nanoseconds. This is the result of parasitic inductances and capacitances that reside in the LD and the traces. These are actually a major concern when considering Marks-bank designs as will become clear shortly.

To explore the driver capabilities for laser diode stimulation, Laser Component's ADL-65075TL (continuous mode laser, 14mW, 650nm) was tested with the proposed circuit. The emitter photon flux was captured via a PIN photodiode and the corresponding voltage waveform was taken from a 50Ohm resistor connected in parallel to the photodiode terminals. The waveform is depicted in Figure 3.

Notice that the signal resembles strongly the output voltage presented in Figure 2. However, it has both fast leading and falling edges, which indicates that the laser diode is emitting light only during the semi-Gaussian part of output signal. A peculiar effect of the parasitic inductances is the negative voltage observed in Figure 3 following the Gaussian signal. Depending on the used resistor this effect can be augmented or reduced significantly.

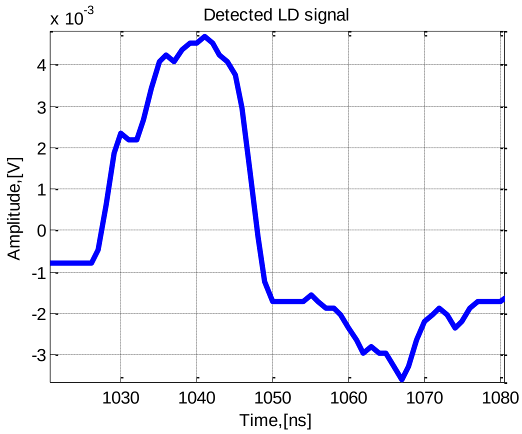

Figure 3. Measured laser diode signal with a PIN photodiode

3. THE MARKS-BANK DESIGN

Avalanche transistors are often combined in Marks-Bank designs [7,11], since powerful PLDs may require tens of amperes of forward current for optimal operation [10]. Here a similar approach is followed through a combination of several single transistor drivers.

3.1. The parallel stack

Initially a parallel configuration was studied consisting of three single transistor drivers, with the supply voltage and input pulses kept the same as before. To achieve better stability a modification with respect to the standard circuit is made as resistors are connected to each of the transistor emitters. The modified circuit is depicted in Figure 4.

The waveform depicted in Figure 5 is the output voltage drop across the laser diode. Notice that there are three distinct peaks accounting for the avalanche process occurring in each transistor. Considering that a 1cm trace on a 0.8 mm thick FR4 substrate introduces a delay of about 70ps and that positioning three identical avalanche transistor drivers on a 2D plane is hardly possible, this result is not surprising. As a result the breakdown process occurs at a slightly different moment of time with the amplitude never reaching a peak and stretching the signal length. It is not hard to imagine that the problem will worsen with the increase of the transistor count.

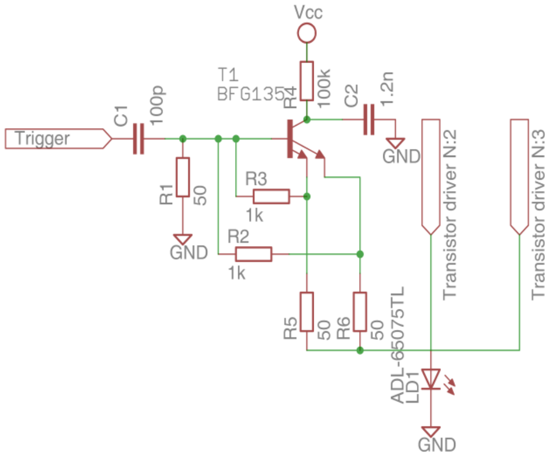

Figure 4. The parallel stack topology

3.2. The sandwich topology

To overcome the difficulty of trace length differences the Marks-Bank driver can be laid outs as a three part sandwich structure – a bottom PCB, holding the laser diode and the emitter resistors, up to eight identical vertically mounted PCBs (each of which represents a single transistor driver) and a closing top PCB that supplies the power and trigger pulses. Integrating the three parts can produce a compact laser diode driver and initial study of the structure shows good driving capabilities.

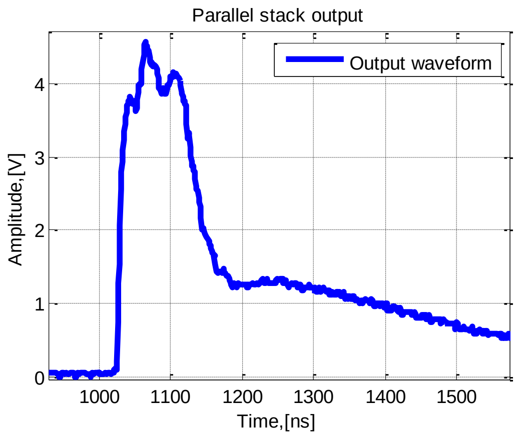

Figure 5. Output waveform of the parallel stack

4. CONCLUSION

Avalanche transistors are an interesting and promising alternative to laser diode excitation. A single transistor driver is shown to be capable of switching up to several hundreds of mA in 30ns. By changing the energy storage capacitor value the current switching capabilities can be easily modified, as well as the output signal length. The single transistor driver serves as the building block for the more powerful Marks-Bank driver which when constructed by three separate identical single transistor drivers was found to be capable of generating relatively strong output signals across the laser diode. However, it suffers from synchronization issues, due to differences in signal paths, which led to the consideration of a custom topology for the driver where the introduced delay is identical for each single transistor block. It is through this design that high current switching can be achieved and efficient photoacoustic signal generation can be made possible.

5. ACKNOWLEDGMENTS

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