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# Comparison of the leading-edge timing walk in pulsed TOF laser range finding with avalanche bipolar junction transistor (BJT) and metal-oxide-semiconductor (MOS) switch based laser diode drivers

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Timing walk error in pulsed time-of-flight based laser range finding was studied using two different types of laser diode drivers. The study compares avalanche bipolar junction transistor (BJT) and metal-oxide-semiconductor field-effect transistor switch based laser pulse drivers, both producing 1.35 ns current pulse length (full width at half maximum), and investigates how the slowly rising part of the current pulse of the avalanche BJT based driver affects the leading edge timing walk. The walk error was measured to be very similar with both drivers within an input signal dynamic range of 1:10 000 (receiver bandwidth of 700 MHz) but increased rapidly with the avalanche BJT based driver at higher values of dynamic range. The slowly rising part does not exist in the current pulse produced by the metal-oxide-semiconductor (MOS) based laser driver, and thus the MOS based driver can be utilized in a wider dynamic range. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/1.4999253>

## I. INTRODUCTION

The pulsed time-of-flight (TOF) laser range finding techniques operate by sending a short laser pulse to the target and measuring the time interval between the submitted pulse and the reflected echo (see Fig. 1). Typically, pulses with a length of a few nanoseconds generated with a laser diode are used in industrial instrumentation.<sup>1–6</sup> The pulse length is determined as a trade-off between the needed optical pulse power (typically 10 W or more) and the speed of the high current (>10 A) high-speed (ns-scale) electrical drivers needed to pulse the laser diode.<sup>1,4</sup>

The receiver of a pulsed time-of-flight laser radar usually consists of an avalanche photodiode (APD) detector, a low-noise preamplifier, limiting amplifiers, and a timing comparator transforming the weak “analogue” echo signal to a digital timing mark for the time interval measurement. If straightforward leading edge detection is utilized in the timing comparator, timing walk error is introduced, as the amplitude of the echo usually varies a lot as a function of the target distance  $R$  (typically proportionally to  $1/R^2$ ), reflectivity, and orientation of the object. One part of this error originates from the geometrical error, as shown in Fig. 2, and the other part originates from the varying group delay of the receiver channel for different pulse leading edge speeds.<sup>7,8</sup> The geometrical error arises from the finite slow rate of the optical laser pulse and can thus be lowered by increasing the edge speed of the pulse. As a zero-order approximation, the electric delay of the receiver channel is proportional to the bandwidth of the channel: the higher the bandwidth, the smaller the delay and thus also the timing walk. Typically, however, the bandwidth of the receiver channel is matched with the laser pulse to optimize the signal-to-noise ratio (SNR) in pulse detection. In practical realizations, with laser pulses ~3 ns [full width at

half maximum (FWHM)] in length, a receiver bandwidth of ~200 MHz is used, and the corresponding timing walk is ~2 ns in a dynamic range of 1:100 000.<sup>6</sup> Many different techniques have been suggested to minimize the timing walk, e.g., the measurement of the pulse width and/or rise time or the pulse amplitude and using this information for timing walk error compensation based on prior calibration. These techniques have resulted in cm-level accuracy in a wide range of pulse amplitude echoes, e.g., in a range of 1:10 000.<sup>6,9–16</sup>

The purpose of this work is to experimentally show that in addition to these well-known timing walk error sources, the laser driving scheme also affects the timing walk. More specifically, it is shown that an avalanche driver, which is typically used for high-speed/high-power driving of semiconductor laser diodes, also introduces a relatively slowly rising current component to the high-speed switching current. This component slows down the edge speed of the optical output from the laser diode with the result of increased timing walk, especially for very large echoes for which the timing threshold is at the root of rising the optical pulse. On the other hand, a metal-oxide-semiconductor (MOS) based driver does not produce this slow component, and thus the total timing walk is lower.

## II. EXPERIMENT

### A. Laser transmitter configurations

Typically, laser diode drivers working at relatively high currents (>10 A) and high-speed pulses (<5 ns pulse width) utilize the LCR transient approach depicted in Fig. 3.<sup>17,18</sup> In this mode, a capacitor is first charged to a high voltage of approximately 150–300 V and then discharged through a semiconductor switch. Since the circuit inevitably also includes some inductance (e.g., laser diode and switch bonding wires,

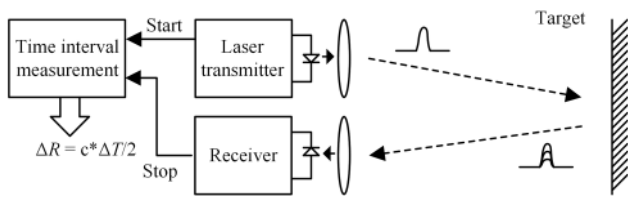


FIG. 1. Block diagram of a pulsed time-of-flight laser radar.

typically a few nH), the resulting resonance in the current waveform is damped with a series resistor  $R_D$ , which is typically selected to match with  $(L/C)^{1/2}$  for optimum damping. In this configuration, the pulse width and amplitude are

$$\Delta t_{\text{pulse}} \approx 2.2\sqrt{LC_1}, \quad I_{\text{peak}} \approx \frac{V_{CC}}{R_D + \sqrt{\frac{L}{C_1}}}, \quad (1)$$

respectively. The nice feature of this circuit is that the pulse width can be set based on the circuit parameters ( $C_1$ ) without the need to accurately control the length of the ON period of the current switch. On the other hand, the power efficiency of the circuit is not particularly good. For example, with a supply voltage of 150 V, an inductance  $L$  of 4 nH, and a capacitor  $C_1$  of 40 pF, current pulses with a peak amplitude and pulse width of  $\sim 7.5$  A and  $\sim 1$  ns can be produced.

Owing to its high-speed switching properties, a typical selection for the semiconductor switch in the driver configuration of Fig. 3 is an avalanche transistor. The switching of an avalanche transistor is a rather complicated 2D phenomenon and has been quite extensively studied in the literature.<sup>19–24</sup> From the practical point of view, an avalanche transistor is an NPN bipolar junction transistor (BJT), whose collector is biased above the collector-base pn-junction breakdown limit. When its base-emitter circuit is driven with a proper triggering signal, a high-speed breakdown occurs, resulting in a step-like change in the collector voltage from the bias voltage  $V_{HV}$  to a residual voltage typically of a few tens of volts.<sup>19</sup> This voltage step introduces a similar step across the laser diode in the driver configuration of Fig. 3, and thus a large pulse current, as discussed above, is generated through the laser diode.

Another option for the driver switch is a MOS transistor, which is typically used especially for longer current pulse widths ( $> 5$  ns).<sup>25</sup> It is shown elsewhere, however, that the pulsing scheme of Fig. 3 also allows, using a properly driven MOS based switch, current pulses of  $\sim 1$  ns at the peak current level

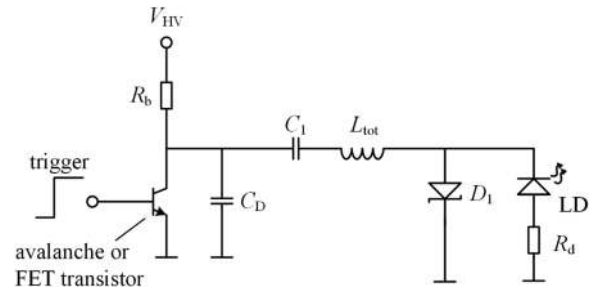


FIG. 3. A schematic of a pulsed laser diode transmitter based on the LCR current transient driver.

of  $\sim 10$  A limited by the maximum allowed drain voltage of the switch.<sup>18</sup>

To compare possible differences in pulsed TOF measurement performance when using an avalanche transistor or a metal-oxide-semiconductor field-effect transistor (MOSFET) based transmitter, two laser driver boards were made with as similar a current pulse shape as possible, one with an avalanche transistor and another with a MOSFET. The avalanche transistor based driver was realized using the scheme of Fig. 3 with the FMMT415 (Zetex) avalanche transistor and a supply voltage of 290 V ( $C_D = 45$  pF,  $C_1 = 45$  pF,  $R_d = 4.7$   $\Omega$ ). The MOSFET based transmitter used an FDMC86244 (Fairchild) MOSFET as the switch with the same scheme, but with a supply voltage  $V_{HV}$  of 150 V ( $C_1 = 78$  pF,  $R_d = 4.7$   $\Omega$ ). These parameters led to a similar current pulse amplitude of  $\sim 10$  A and a current pulse width of  $\sim 1.35$  ns (FWHM) with both drivers. The measured current waveforms and the corresponding optical laser outputs (measured with an optical probe with a bandwidth of 12 GHz and 1 GHz, respectively) are shown in Fig. 4. The same type of commercial double-heterostructure (DH) AlGaAs laser diode with a nominal peak power of  $\sim 8$  W at 10 A peak current with 150  $\mu\text{m}$  strip width and 905 nm center wavelength was used in both transmitters.

Comparing the drive currents in Fig. 4(a), the notable feature in the current pulse generated with the avalanche transistor driver is the slowly rising front edge whose speed, however, increases markedly after the initial transient. The shape is very typical for avalanche based current switches, as is seen in previous studies as well, e.g., in Refs. 24 and 26. In the MOS based driver, the front edge of the current pulse does not have the slowly rising part. Note also that since the MOS switch does not show the residual voltage typical for an avalanche BJT switch, the supply voltage and consequently also the power

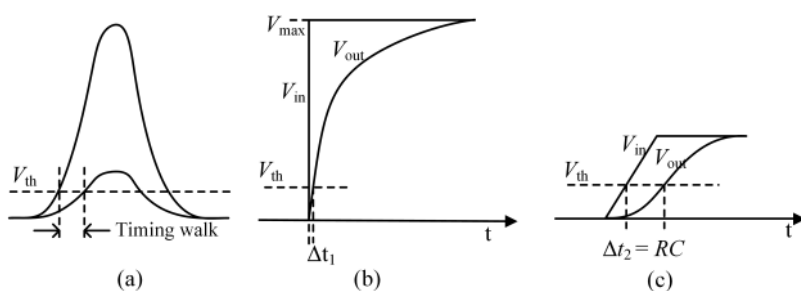


FIG. 2. (a) Timing walk due to varying echo amplitudes, (b) timing walk with extremely large echo amplitudes, and (c) electrical delay in the case of a small input signal.

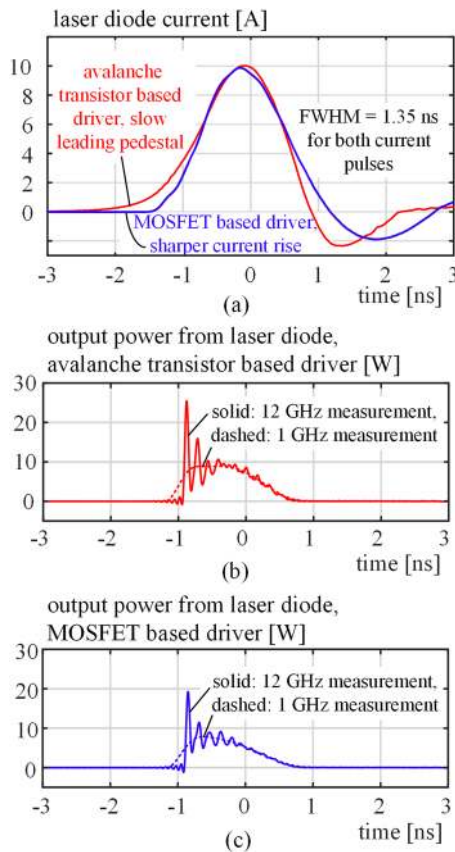


FIG. 4. (a) Measured drive currents for the avalanche BJT and MOSFET based current pulses, and the corresponding optical output of the laser diodes as a function of time: (b) avalanche transistor based pulses and (c) the MOSFET based pulses, with two measurement bandwidths shown.

consumption are lower. Even more importantly, since the power consumed by the MOS switch is lower, the pulsing rate of the MOS switch based driver can be higher (e.g., 100 kHz ... 1 MHz versus <10 kHz). It is also to be noted that since the avalanche breakdown sets the requirement for the operating voltage, the high-speed switching, somewhat surprisingly, cannot be realized in this mode at lower current levels, e.g., <5 A with the avalanche transistor based driver, since the lowering of the current necessitates the use of a higher value for the damping resistor, and thus the current would follow the resistor-capacitor (RC)-transient mode.

The measured optical output pulse shapes are quite similar; the peak powers are about ~10 W and the pulse lengths are about ~1.1 ns (FWHM) for both transmitters [Figs. 4(b) and 4(c)]. The optical measurements with the higher bandwidth of 12 GHz show strong relaxation oscillations in the optical output of this particular laser diode. At the lower bandwidth of 1 GHz (roughly corresponding to the bandwidth of the APD), the oscillations are averaged out. Note, however, that due to the strong relaxation oscillations, the optical input of the receiver channel is a quasi-step, which reduces the timing walk, as explained above. The tendency of a laser diode to go into relaxation oscillations depends on its “equivalent spot size” or  $d_a/\Gamma$  ( $d_a$  thickness of active region,  $\Gamma$  confinement factor), as is discussed in detail in Ref. 27.

## B. Timing walk error

The timing walk was measured using a pulsed time-of-flight laser range finder configuration shown in Fig. 5. The receiver used was a customized receiver IC (integrated circuit) implemented in a 0.18  $\mu\text{m}$  high voltage complementary metal-oxide-semiconductor (HVC MOS) technology.<sup>28</sup> The bandwidth and transimpedance of the receiver are 700 MHz and 25 k $\Omega$ , respectively. The total input referred noise current is approximately 450 nA<sub>rms</sub> with a discrete APD (diameter 100  $\mu\text{m}$ ,  $C_{in,total}$  0.5 pF) at the input of the receiver channel. The receiver includes a transimpedance preamplifier, a post-amplifier, and a timing comparator discriminating the timing point from the leading edge of the received echo pulse. The start-stop time intervals were measured with a full-custom CMOS time-to-digital converter (TDC) with ~10 ps single-shot precision.<sup>29</sup> The results were transferred to a personal computer (PC) through a field-programmable gate array (FPGA) based universal serial bus (USB) connection.

The pulsed TOF range finder was set to measure a non-cooperative target located at a constant distance, and the amplitude of the received echo pulse (and thus the peak value of the APD pulse current) was varied using absorptive neutral density (ND) filters. The timing point of the rising edge of the received echo was calculated at each signal level by averaging 10 000 successive single-shot results. The threshold for the timing discrimination was set to be SNR = 7, and the height of the received echo pulse was swept from SNR = 10 to SNR = 2 000 000, giving the dynamic range of 1:200 000. The measured timing walk, i.e., the variation of the detected timing point as a function of the amplitude of the received echo, was measured for both laser pulse transmitters presented above. The measured change of the timing point as a function of the input signal amplitude (presented as SNR), i.e., the timing walk error, is shown in Fig. 6.

Within the dynamic range of 1:10 000, the total timing walk for both drivers is more or less equal (~600 ps). This error is, as explained above, coming mostly from the changing electric delay of the receiver channel for pulses with a different amplitude. The receiver consists of 3 stages with a bandwidth of 1.2 GHz each, and thus the total delay for the smallest signals (linear operation regime) is ~650 ps (~3 $\times$ RC<sub>stage</sub>).

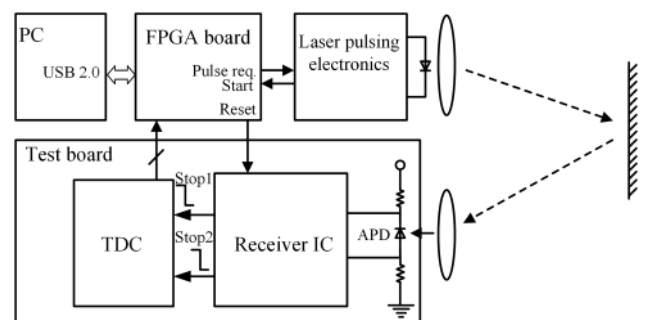


FIG. 5. A more detailed block diagram of the timing walk measurement environment.

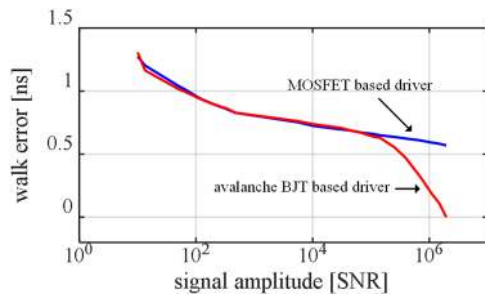


FIG. 6. Measured timing walk error for the MOSFET and avalanche BJT based drivers (the avalanche BJT-based driver has a significantly greater walk error due to spontaneous emission at the leading edge of the laser pulse caused by a slower rising edge of the current pulse).

For high-amplitude signals, the delay is very small and thus the total walk is defined by the maximum delay.

Note, however, that for larger signals (above  $\text{SNR} \sim 10^5$ ), the timing walk achieved with the avalanche transistor based driver increases much faster than with the MOS based driver, at about  $\sim 400$  ps per decade. We associate this behavior with the slow initial rise of the driving current in the avalanche BJT based driver, which results in slower build-up of the lasing process in the laser diode, and thus in slower initial rise of the optical signal.<sup>21</sup> As a result, when the signal amplitude is so large that the reference level of the comparator probes this part of the optical pulse, the timing walk increases.

### III. CONCLUSIONS

We have compared the drive currents and optical output pulse shapes of avalanche BJT switch and MOSFET switch based laser diode drivers working in the LCR transient mode. The transmitters were used to drive a commercial DH pulsed laser diode, which gave an optical peak output power of  $\sim 10$  W and a pulse length of  $\sim 1.1$  ns with a peak driving current of  $\sim 10$  A. It is shown that although the basic shape of the driving current is quite similar in both the avalanche BJT and MOS based drivers, the former has a slowly rising part in its output current which, however, is not seen with the MOS switch based driver.

Moreover, accurate timing walk measurements realized in a pulsed TOF laser radar configuration within a wide dynamic range show that for high signal amplitudes exceeding the dynamic range of  $\sim 1:10\,000$ , the timing walk of the system utilizing the avalanche BJT switch based driver increases markedly ( $\sim 400$  ps per decade) compared to the system using a MOS switch based laser diode driver. We also showed that the developed pulsed time-of-light laser radar system can achieve a total timing walk error of  $\sim 700$  ps within a dynamic range of  $1:100\,000$  of signal amplitudes. This is markedly lower than what was achieved in earlier studies, e.g., 2.2 ns in Ref. 6. The improvement was partly achieved by increasing the edge speed of the laser diode output and the bandwidth of the receiver channel (however, at the expense of increased noise) and partly because of the higher switching speed of the MOS based driver with the used current and pulse length parameters.

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- <sup>1</sup>J. Kostamovaara, K. Määttä, M. Koskinen, and R. Myllylä, "Pulsed laser radars with high modulation-frequency in industrial applications," *Proc. SPIE* **1633**, 114 (1992).
- <sup>2</sup>G. Zhou, M. Li, L. Jiang, C. Li, N. Liu, Y. Sun, and T. Yue, "3D image generation with laser radar based on APD arrays," in *IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (IEEE, 2015), p. 5383.
- <sup>3</sup>I. Kaisto, J. Kostamovaara, M. Manninen, and R. Myllylä, "Optical range finder for 1.5–10-m distances," *Appl. Opt.* **22**(20), 3258 (1983).
- <sup>4</sup>H. N. Burns, C. G. Christodoulou, and G. D. Boreman, "System design of a pulsed laser rangefinder," *Opt. Eng.* **30**(3), 323 (1991).
- <sup>5</sup>P. Palojärvi, K. Määttä, and J. Kostamovaara, "Pulsed time-of-flight laser radar module with millimeter-level accuracy using full custom receiver and TDC ASICs," *IEEE Trans. Instrum. Meas.* **51**(5), 1102 (2002).
- <sup>6</sup>S. Kurtti, J. Nissinen, and J. Kostamovaara, "A wide dynamic range CMOS laser radar receiver with a time-domain walk error compensation scheme," *IEEE Trans. Circuits Syst., I* **64**(3), 550 (2017).
- <sup>7</sup>R. J. V. Plassche and P. Baltus, "An 8-bit 100-MHz full-Nyquist analog-to-digital converter," *IEEE J. Solid-State Circuits* **23**(6), 1334 (1988).
- <sup>8</sup>P. Palojärvi, T. Ruotsalainen, and J. Kostamovaara, "A 250-MHz Bi-CMOS receiver channel with leading edge timing discriminator for a pulse time-of-flight laser rangefinder," *IEEE J. Solid-State Circuits* **40**(6), 1341 (2005).
- <sup>9</sup>T.-H. Ngo, C.-H. Kim, Y. J. Kwon, J. S. Ko, D.-B. Kim, and H.-H. Park, "Wideband receiver for a three-dimensional ranging LADAR system," *IEEE Trans. Circuits Syst., I* **60**(2), 448 (2013).
- <sup>10</sup>M. Ghioni, S. Cova, C. Samori, and F. Zappa, "True constant fraction trigger circuit for picosecond photon-timing with ultrafast microchannel plate photomultipliers," *Rev. Sci. Instrum.* **68**, 2228 (1997).
- <sup>11</sup>H.-S. Cho, C.-H. Kim, and S.-G. Lee, "A high-sensitivity and low-walk error LADAR receiver for military application," *IEEE Trans. Circuits Syst., I* **61**(10), 3007 (2014).
- <sup>12</sup>T. Ruotsalainen, P. Palojärvi, and J. Kostamovaara, "A current-mode gain-control scheme with constant bandwidth and propagation delay for a transimpedance preamplifier," *IEEE J. Solid-State Circuits* **34**(2), 253 (1999).
- <sup>13</sup>T. Ruotsalainen, P. Palojärvi, and J. Kostamovaara, "A wide dynamic range receiver channel for a pulsed time-of-flight laser radar," *IEEE J. Solid-State Circuits* **36**(8), 1228 (2001).
- <sup>14</sup>J. Pehkonen, P. Palojärvi, and J. Kostamovaara, "Receiver channel with resonance-based timing detection for a laser range," *IEEE Trans. Circuits Syst.* **53**(3), 569 (2006).
- <sup>15</sup>J. Nissinen, I. Nissinen, and J. Kostamovaara, "Integrated receiver including both receiver channel and TDC for a pulsed time-of-flight laser rangefinder with cm-level accuracy," *IEEE J. Solid-State Circuits* **44**(5), 1486 (2009).
- <sup>16</sup>A. Kilpelä, J. Ylitalo, K. Määttä, and J. Kostamovaara, "Timing discriminator for pulsed time-of-flight laser ranging measurements," *Rev. Sci. Instrum.* **69**(5), 1978 (1998).
- <sup>17</sup>A. Kilpelä and J. Kostamovaara, "Laser pulser for a time-of-flight laser radar," *Rev. Sci. Instrum.* **68**(6), 2253 (1997).
- <sup>18</sup>L. Hallman, J. Huikari, and J. Kostamovaara, "A high-speed/power laser transmitter for single photon imaging applications," in *IEEE SENSORS 2014 Proceedings* (IEEE, 2014), p. 1157.
- <sup>19</sup>S. Vainshtein, V. Yuferev, and J. Kostamovaara, "Avalanche transistor operation at extreme currents: Physical reasons for low residual voltages," *Solid-State Electron.* **47**(8), 1255 (2003).
- <sup>20</sup>A. S. Kesar, L. M. Merensky, M. Ogranovich, A. F. Kardo-Sysoev, and D. Shmilovitz, "6-kV, 130-ps rise-time pulsed-power circuit featuring cascaded compression by fast recovery and avalanche diodes," *Electron. Lett.* **49**(24), 1539 (2013).
- <sup>21</sup>S. Vainshtein, V. Yuferev, and J. Kostamovaara, "Nondestructive current localization upon high-current nanosecond switching of an avalanche transistor," *IEEE Trans. Electron Devices* **50**(9), 1988 (2003).

- <sup>22</sup>M. Inokuchi, M. Akiyama, T. Sakugawa, H. Akiyama, and T. Ueno, "Development of miniature Marx generator using BJT," in *2009 IEEE Pulsed Power Conference* (IEEE, 2009), p. 57.
- <sup>23</sup>S. Vainshtein, V. Yuferev, and J. Kostamovaara, "Analyses of the picosecond range transient in a high-power switch based on a bipolar GaAs transistor structure," *IEEE Trans. Electron Devices* **52**(12), 2760 (2005).
- <sup>24</sup>G. Duan, S. Vainshtein, and J. Kostamovaara, "Lateral current confinement determines silicon avalanche transistor operation in short-pulsing mode," *IEEE Trans. Electron Devices* **55**(5), 1229 (2008).
- <sup>25</sup>K. Ito, C. Niclass, I. Aoyagi, H. Matsubara, M. Soga, S. Kato, M. Maeda, and M. Kagami, "System design and performance characterization of a MEMS-based laser scanning time-of-flight sensor based on a 256 times 64-pixel single-photon imager," *IEEE Photonics J.* **5**(2), 6800114 (2013).
- <sup>26</sup>B. Lanz, B. Ryvkin, E. Avrutin, and J. Kostamovaara, "Performance improvement by a saturable absorber in gain-switched asymmetric-waveguide laser diodes," *Opt. Express* **21**(24), 29780 (2013).
- <sup>27</sup>B. Ryvkin, E. Avrutin, and J. Kostamovaara, "Asymmetric-waveguide laser diode for high-power optical pulse generation by gain switching," *IEEE/OSA J. Lightwave Technol.* **27**(12), 2125 (2009).
- <sup>28</sup>M. Hintikka and J. Kostamovaara, "A CMOS laser radar receiver for sub-ns optical pulses," in *2015 11th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME)* (IEEE, 2015), p. 176.
- <sup>29</sup>J. Jansson, V. Koskinen, A. Mäntyniemi, and J. Kostamovaara, "A multi-channel high precision CMOS time-to-digital converter for laser-scanner-based perception systems," *IEEE Trans. Instrum. Meas.* **61**(9), 2581 (2012).