# Nonlinear MSM Photodetector Model for High Resolution Laser Impulse Radar Imaging

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*Abstract:* **-** Based on the recently developed modulation scheme of highly dynamic and strong carrier injection into the active zone of a single-heterostructure (SH) laserdiode, laser pulses of some hundreds of watts and pulse widths (FWHM) of about 30 ps are available. Such optical pulses are useful for high precision near-field ranging. Until now suitable optical receivers are not available. This paper concerns a broadband optical receiver using a very fast large area MSM photodiode. We present nonlinear CAD Models for photodiode derived from measurement which can be to analyze the nonlinear transfer function versus the optical large signal stimulus. Accurate models correction of the distorted signals can be performed to making time interval measurement more accurate. Measurement uncertainties in the micrometer range could be attained by data range error correction using a nonlinear equivalent network for the device. The results are demonstrated on the basis of 2D and 3D mapped objects.

*Key-Words:* **-** Nonlinear, MSM, Photodiode, Laser, Impulse, Radar, Distance, 3D, Imaging.

## 1 Introduction

The performance of laser impulse radar (LIR) systems has continuously improved during the last two decades. Such systems are destined to quality control [1], distance and contour mapping [2, 3] or involved to acquire medical images as 3D surface points of anatomical part to be operate [4]. In particular a developed modulation scheme [3] has led to ultra short optical pulses which require corresponding broadband receiving units. Different approaches are known [2, 5]. One main problem of highly precise measurements originates in the nonlinearities of the used photodiodes [6]. In many investigations, discussing the phase difference ranging approach, a phase uncertainty of about 55 degree has been observed under high dynamics of the received signal. For PIN detectors more than 5 degree phase shifting versus input signal amplitude can be measured. Therefore, submillimeter uncertainties are rather difficult to be obtained without taking into account the device nonlinearities. We have also observed similar effects utilizing pulse-traveling ranging methods. Ranging errors of several millimeters are observed with high received signal dynamics, which originate from the nonlinearities of the photodiode used. Fig.1 shows the time significant point, defined in this case at 40 % of the amplitude, varies with the received optical power. Therefore exact knowledge of the nonlinearities of the photodiodes and the following amplifier is strongly needed to access the submillimeter and micrometer measurement uncertainty range. Commonly, avalanche photodiodes are used in laser impulse radar (LIR) systems with typical rise time of about 240 ps. In this paper and for the first time an MSM photodiode with much higher bandwidth is used in a short range LIR. It is shown that an MSM photodiode based LIR has superior performance with respect to ranging uncertainty.

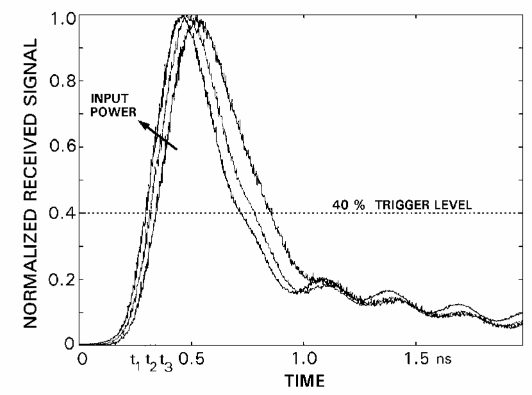


**Fig. 1:** Measured received pulse response of a laser radar system for different optical power

## 2 Nonlinear Model of MSM Photodiode

Regarding precise LIRs for 3D imaging, the nonlinearities of the used photodiode must be taken into account. The model consists of a physics-based O/E-converter (physical part) and an electrical network with nonlinear current, charge sources and series resistance (Fig. 2) [7].

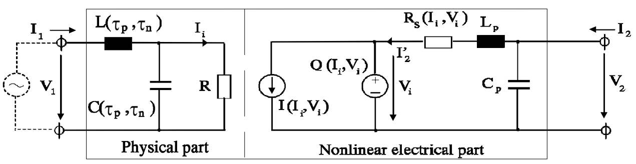


Fig. 2: Lumped element nonlinear model of a MSM photodiode

The nonlinear transfer function of the ideal MSM photodiode converter similar to [8, 9, and 10] may be written as follows:

$$H_{oe}(\omega)=\frac{a_n^2}{\left(e^{-a_n}+a_n-1\right)}\frac{1}{\left(a_n+j\omega\tau_n\right)}\left[\frac{e^{-\left(a_n+j\omega\tau_n\right)}-1}{\left(a_n+j\omega\tau_n\right)}+1\right]+\frac{a_p^2}{\left(e^{-a_p}+a_p-1\right)}\frac{1}{\left(a_p+j\omega\tau_p\right)}\left[\frac{e^{-\left(a_p+j\omega\tau_p\right)}-1}{\left(a_p+j\omega\tau_p\right)}+1\right] \quad (1)$$

This equation characterizes the generation of the electron-hole pairs and the drift of the carriers in the depletion layer.

$\tau_n$ and $\tau_p$ are the electron and hole transit times. are $a_n$ and $a_p$ are the respective transit time to lifetime ratios ($a_n = \tau_n / \tau_e$, and $a_p = \tau_p / \tau_h$, with $\tau_e$ and $\tau_h$ the electron and hole lifetime, respectively). When $\tau_e >> \tau_n$ and $\tau_h >> \tau_p$ and using a Taylor series development eq. (1) can be written as [11]:

$$H(\omega)=1-2\left(\frac{\tau_n+\tau_p}{12}\right)j\omega+3\left(\frac{\tau_n+\tau_p}{12}\right)^2(j\omega)^2+\frac{1}{48}\left(\tau_n-\tau_p\right)^2(j\omega)^2 \quad (2)$$

Eq. 2 may be further rewritten in the following form:

$$H(\omega)=\frac{I_i(\omega)}{V_1(\omega)}\approx\frac{1}{[1+\frac{1}{12}(\tau_n+\tau_p)j\omega]^2} \quad (3)$$

Eq.(3) gives very good approximation up to 25 GHz. Eq.(3) is considered as a second order low pass filter. Using network synthesis approach a lumped-element RLC circuit with $L(\tau_n,\tau_p)$, $C(\tau_n,\tau_p)$ and R (Fig. 3) can be derived from it. The lumped model of the MSM is given in Fig.2. For CAD implementation the optical input power is normalized to $V_1 = (P^i_{opt}/1A)$.

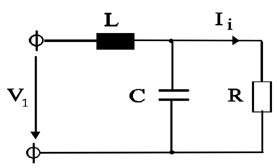


Fig. 3: Equivalent description of eq. (3) by RLC network ($V_1 = P^i_{opt}/1A$, $P^i_{opt}$ : Input optical power).

## 3 Model Implementation

First, the small signal elements are extracted from the measured bias dependent electrical reflection coefficient [12]. The nonlinear current and charge sources are obtained by twodimensional integration over the known small signal quantities. They are presented in Figs. 4a-4c. Their bias dependent values are implemented in MDS (Microwave Design System) as Citi-Files (two-dimensional look-up tables). The nonlinear lumped element model of Fig. 2 is implemented in MDS. The nonlinear elements are modeled in MDS as a six port symbolically defined device (SDD) and the residual linear elements as a lumped elements circuit. All parameters needed for the simulation are in the circuit page. The data for the bias dependent elements are spline-interpoled from data-set variables. The relation between the different parameters are implemented as equations. The model is used for a transient pulse simulation.

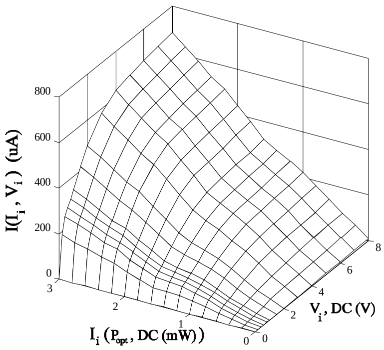


Fig. 4a: Current source $I(I_i,V_i)$

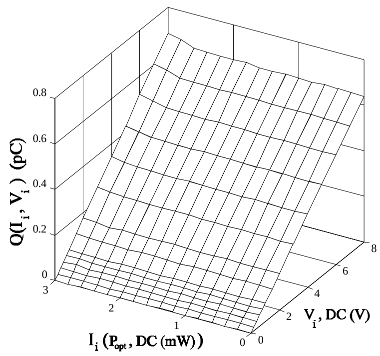


Fig. 4b: Charge source $Q(I_i,V_i)$

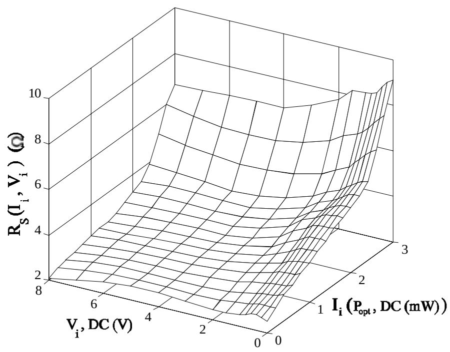


Fig. 4c**:** Small signal series resistance $R_S(I_i,V_i)$

In Fig. 5 the measured and the simulated pulse response are presented. The Inset figure of Fig. 5 is the optical input pulse with $t_{rise}$= 24 ps and $t_{FWHM}$ = 35 ps.

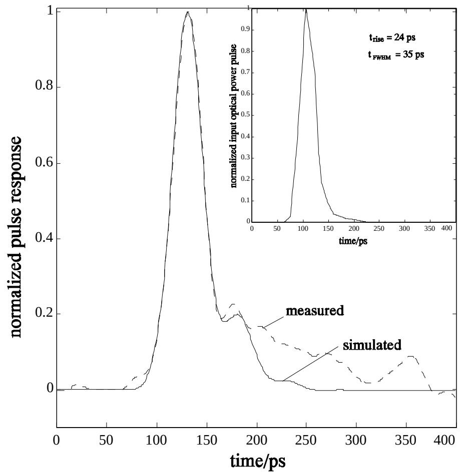


Fig. 5: Simulated and measured pulse response of MSM Photodiode (60µm x 60µm)

## 4 Laser Radar Set Up

Figure 6 shows a schematic view of a pulsed laser radar setup [13]. The laser beam from the laser transmitter is focused via scanning mirrors. The pulse is reflected back to the scanning mirrors, collected and focused by the receiver optics onto the photodetector. In addition, the reference signal is reflected back by a reference-pulse mirror and focused onto the photodetector. The distance to the illuminated point on the target can be calculated from the time interval between the detected reference and the measured signal (Fig. 8), where the time is proportional to the distance. As a laser transmitter, a laser diode LD-60 with a small emission stripe of 76.2 µm is used [3]. The pulse repetition frequency is typically 40 KHz.

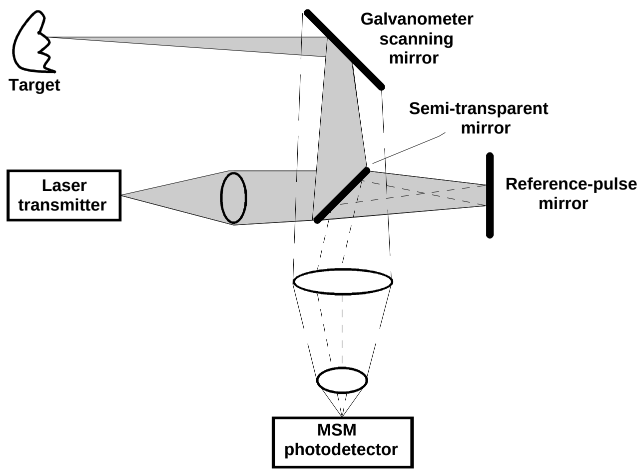


Fig. 6: Schematic of the pulsed laser radar

## 5 Distance Measurements

Constant distance is measured using a large area (200µm x 200µm) MSM Photodetector. The measurement is repeated 100 times using 16-point averaging in each case Fig7. The measurement uncertainty is about 156 µm. Fig. 8 shows the detected pulse for the distance measurement. One of the advantages of using the MSM photodiode is the short tail of the received pulse which leads to less interference between the reference and received pulses. As a result time-measurement window can be used which improves the radial resolution of the measurements and shortens the measurement range.

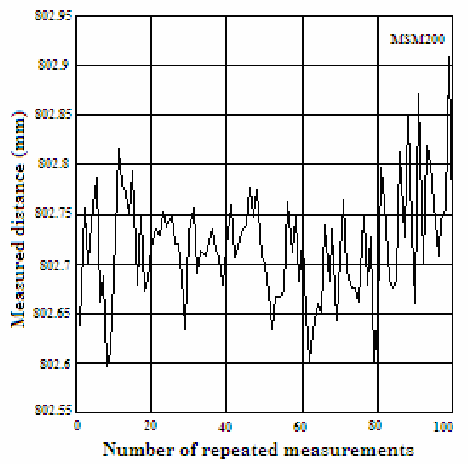


Fig. 7: Distance measurements (uncertainty = 156.26 µm)

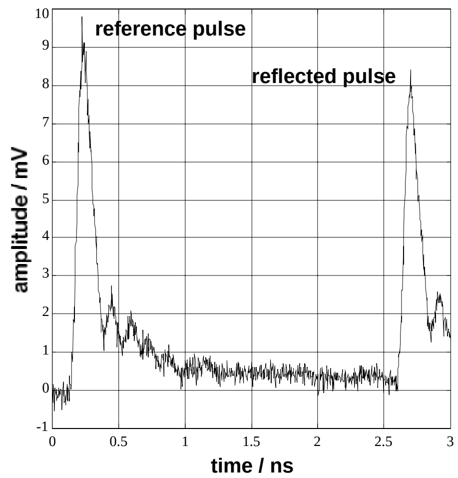


Fig. 8 Detected pulses for distance of a MSM photodiode (Active area: 200µm x 200µm).

The distribution of the distance measurements versus the distance deviation is presented in Fig. 9. The standard deviation range is 56 µm.

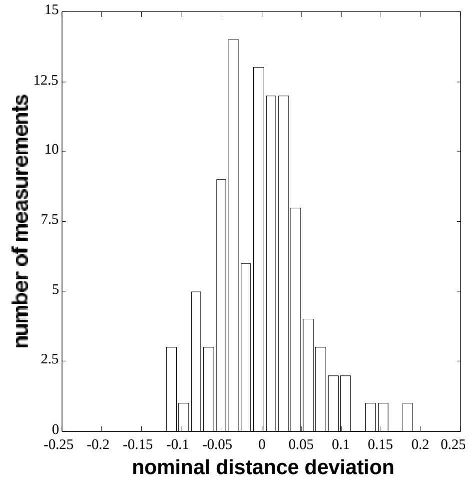


Fig. 9: Distribution of the distance deviation ($\sigma_{MSM}$ = 56.53 µm)

## 6 2D and 3D Applications

Figures 10 and 11 show the scanned small salt shaker, imaged from a distance of 40 cm, as intensity and wireframe images, respectively. The lateral resolution is 0.5 mm in both directions. The black area in Fig. 10 represents a holder which was used to clamp the model shaker in place during the scanning process.

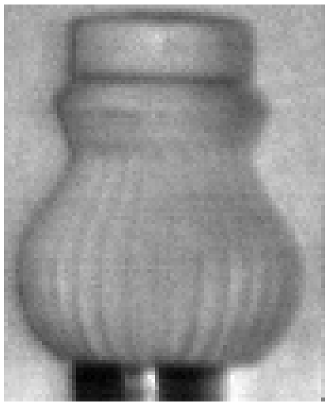

Fig. 10: Scanned image of a small salt shaker
Real size: 42.5x52.5 mm

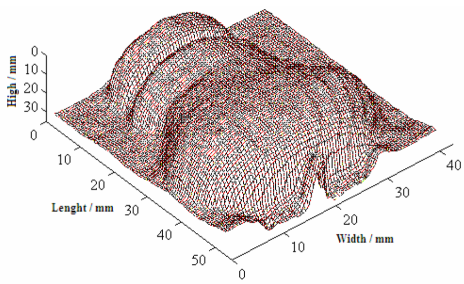


Fig. 11: 3D Wireframe of the small Salt shaker median filtered. Lateral resolution: 0.5 mm
Scan distance: 40 cm

## 7 Conclusion

In this paper an MSM photodiode has been used for near field LIR ranging. The influence of the high signal dynamics on the performance of optoelectronic devices has generally been discussed. Exemplarily, a MSM photodiode has been investigated. Considering this problem there is no principal difference between MSM-, PIN- or avalanche photodiodes. The device can be modelled by a lumped element RLC network with nonlinear current and charge sources derived from measurement. Simulation based on the nonlinear CAD model shows strong influence of the optical input power on the pulseshape of the received electrical signal, and thus, the position of the time significant point for time-interval measurement. Knowing accurate nonlinear device models, error-correction of the distorted received signals can be performed.

It has been shown also that the ranging uncertainty could be drastically reduced in comparison with a radar system that uses an avalanche photodiode in the receiving unit.

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