3D Modeling of a thermo-electric detector array for deconvolution based laser beam profile reconstruction

W. Vandermeiren[a], J. Stiens[a], C. De Tandt[a], G.Borghs[b], E. Delarbre[c], R. Vounckx[a]

[a]Laboratory for Micro- and Photonelectronics, ETRO-FirW
VUB, Pleinlaan 2, B-1050 Brussel, Belgium
[b]IMEC, MCP-division, Kapeldreef 75, B-3001 Leuven, Belgium
[c]Lasercentrum Vlaanderen, Boeretang 200, B-2400 Mol, Belgium

A deconvolution method for optical laser pulse and profile reconstruction is investigated. The thermo-electric detector under consideration has different operation regimes depending on the temporal characteristics of the optical input signal. In mixed regimes, no straightforward reconstruction algorithm exists. Therefore an advanced distributed model was developed using the finite element simulator "Comsol Multiphysics". The model was evaluated with an experimental dataset obtained from high power CO_2 laser measurements. Based on this model a deconvolution algorithm was developed and tested on simulated and experimental datasets. This deconvolution technique used for profile reconstruction is proved by independent experiments to hold.

1. Introduction

CO_2 lasers are widely used for industrial and medical applications. In most of these applications, the laser beam profile determines the processing quality. Therefore, the industrial need exists to measure the laser beam profile at regular basis. The presented detector for this purpose is a thermo-electric (Seebeck) detector array. The operation principle is based on laser induced free carrier absorption in doped GaAs. A temperature gradient is generated as the laser intensity decreases exponentially inside the substrate. This gradient leads to a charge displacement which can be measured (Seebeck voltage). Figure 1 shows the different operation regimes of the detector in function of the temporal behavior of the optical input signal.

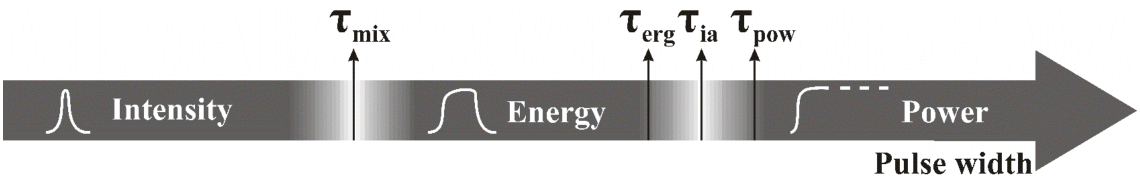

Figure 1: Operation regimes of the Seebeck detector

The electron temperature follows the optical intensity instantaneously for very short pulses as the relaxation time of optically heated electrons is of the order of a few picoseconds [1]. Subsequently, for wider pulses, the electron gas will exchange energy with the lattice allowing the lattice temperature to increase. This lattice heating mechanism is much slower than electron heating. The pulse length for which the electron temperature equals the lattice temperature is called τ_{mix}. For a certain range of pulse widths larger than τ_{mix}, the lattice temperature will increase proportional to the pulse energy. However the energy regime is limited by the thermal response time of the illuminated area (τ_{ia}). As the pulse length approaches τ_{ia}, the lattice temperature will not be able to increase proportionally due to thermal diffusion. For a more detailed description of the operation principle of the Seebeck detector we refer to reference [2]. A trade-off exists between an optimal response in the power-regime and a minimal cross-talk level in the energy regime due to the absence of thermal diffusion. Hence, for profile measurements the optimal performance is reached in the mixed regime (energy-power). In this regime no straightforward reconstruction can be made.

2. FEM simulation & deconvolution

A first attempt to model the system analytically as a lumped-heat-capacity system [3] seemed not appropriate. The detector array cannot be modeled with one fixed time constant as this parameter varies in time in function of the heated volume. Therefore a more advanced distributed model was developed in a finite element method (FEM) simulator "Comsol Multiphysics". Figure 2 illustrates a five pixel detector model (A) and the corresponding lithographic interconnection mask (B). The dark and white regions on this mask are the metallization and absorption regions respectively.

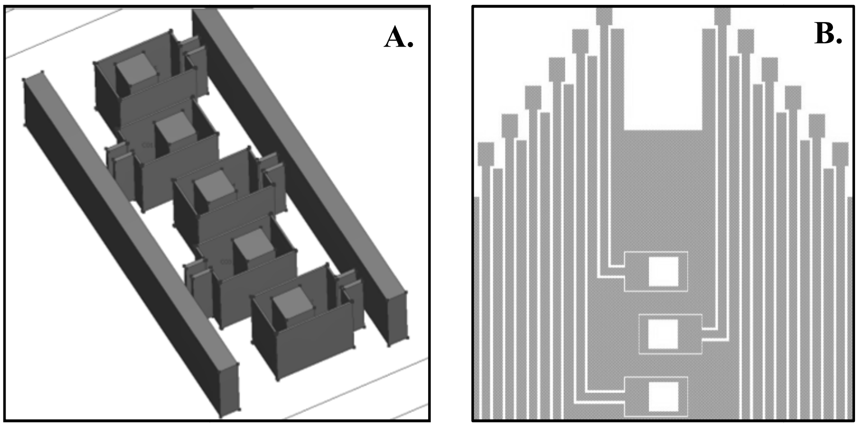

Figure 2: A. 3D Seebeck detector array model: absorption regions; B. Lithographic interconnection mask

The incident laser beam is modeled as a time dependent heat source term Q with an exponential decaying function inside the substrate:

$$Q\left(\frac{W}{m^3}\right) = F_{exposure}(t) * I_0 * \alpha * e^{(\alpha * z)} \qquad (1)$$

Here, I_0 and α are the optical intensity and the absorption coefficient respectively. $F_{exposure}$ models the time dependency of the heat source term. The absorption coefficient α for p-GaAs at a wavelength of 10.6 μm is of the order of $8*10^5$ m^{-1} [4]. The absorption regions (filled regions in figure 2a) were defined in according with the lithographic interconnection mask, except for the interconnect leakage regions along both sides of the detector array, which was approximated by two rectangular absorption regions. The boundaries of the substrate were chosen to be thermally insulating except for the bottom of the sample where a heat transfer coefficient h = 4 kW/(m^2*K) was applied, modeling the combined effect of heat transfer by conduction to the underlying heat sink and forced convection to the water cooling. Simulations pointed out that the thermally insulating boundary approximation is justified as free convection to the air can be neglected with respect to heat transfer by conduction inside the substrate and the heat sink. In order to verify this model an experimental data set was made. One pixel of a Seebeck detector array was scanned with a constant speed (500 mm/s) over a Gaussian laser beam with σ = 2.5 mm and a total power level of 700 W. Hence, the pixel is exposed to a Gaussian pulse with a full width half maximum (FWHM) of $2\sigma\sqrt{\ln(2)} = 8.33\, ms$ which is used as an optical input to the simulator. Figure 3 shows a good agreement between the normalized detector output voltage and the normalized simulator output (temperature evolution). This comparison can be made as a linear relationship between the detector output voltage and the local temperature evolution exist [2]. A relatively low root mean square error (RMS) of 2.59 % proves the validity of our model.

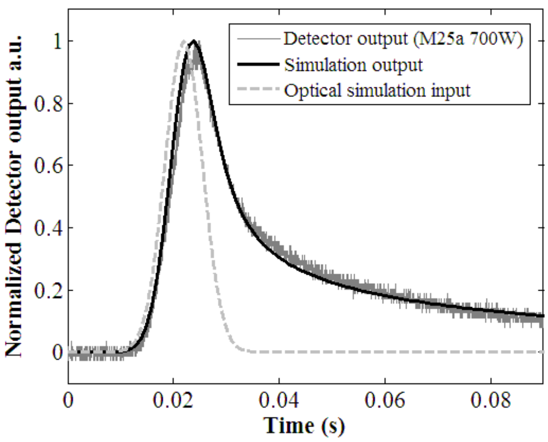

Figure 3: Normalized detector output versus normalized simulation output

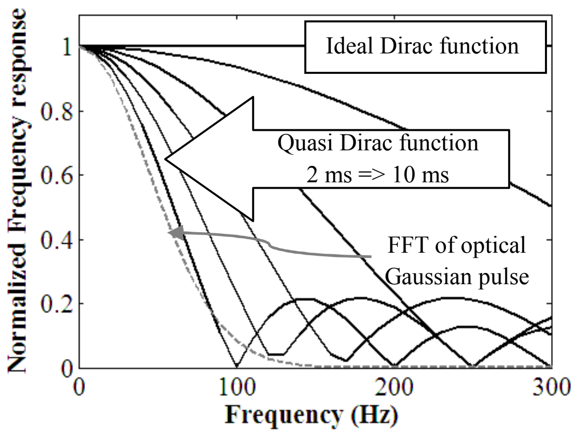

Figure 4: Normalized frequency response of quasi Dirac functions and a Gaussian pulse profile with σ = 5 ms

This model (5 pixel detector array) can be characterized by its impulse response function. The challenge of this numerical approach consists of finding an appropriate quasi Dirac (QD) function as the numerical simulator cannot handle infinite inputs. This QD function is a rectangular pulse of which the width can be optimized for reconstruction purposes of Gaussian pulses with a fixed σ. The QD approximation can be used as long as the frequency content (-3dB) of the signal which has to be reconstructed is significantly smaller compared to the frequency content (-3dB) of the QD function. Hence, the QD pulse width should be as small as possible, approximating the ideal Dirac function. On the contrary, in order for the QD pulse to be representative for the temporal behavior of the system, the QD pulse width should approximate the incident optical pulse width. Figure 4 shows the FFT of different QD functions and a Gaussian pulse with σ = 5 ms which was used in the simulation. Hence, an optimal QD pulse width can be found in function of the frequency content of the optical input pulse with a minimal reconstruction error as shown in figure 5a. These simulations show at the same time the validity of our deconvolution procedure.

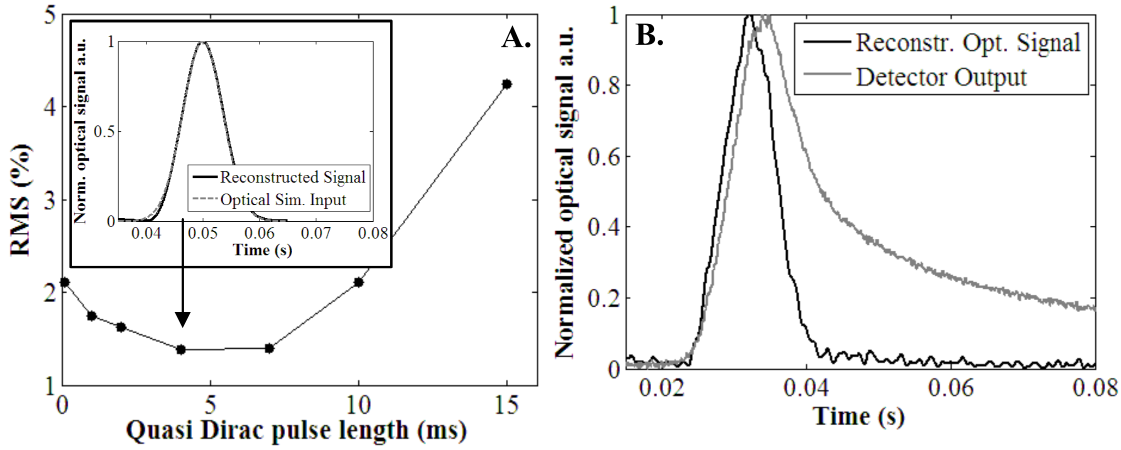

Figure 5: A. Reconstruction RMS in function of the QD pulse length; B. Reconstructed Gaussian laser beam

The minimum RMS is obtained for a QD pulse width close to the incident Gaussian pulse width σ (5 ms) which corresponds to a FWHM 8.33 ms. For non-Gaussian laser beams with higher frequency components, the optimal point will shift to shorter QD pulse lengths. Figure 5b shows the optimized reconstruction of a Gaussian laser beam measurement, with a scanning speed of 500 mm/s and a 2σ laser beam width of 8 mm.

3. Conclusions

The distributed model of a 5 pixel Seebeck detector array was developed in a finite element method (FEM) simulator. The normalized simulator output is in good agreement with the experimental results (RMS of 2.59%). It was shown that the QD pulse width for the impulse response function can be optimized in function of the frequency content and pulse width of the incident laser pulse. For Gaussian pulses an optimum is found around σ. Hence, the scanning speed and an estimate of the laser beam width are required for optimal laser beam reconstruction.

Acknowledgements

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