Signal to Noise Ratio Budget of a Pico-Seconds Pulsed Radar System for Stand-Off Imaging

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***Abstract*— Recently powerful, reliable and cost-effective THz radiation micro-emitters have been developed. These innovative sources have been proven to be capable of providing up to $1\ mW$ of pulsed power in the range of frequencies between 0.1 and $0.7\ THz$. In this paper we present a study of the possible Signal to Noise Ratio using such sources in an ideal non dispersive channel, where the main noise source is assumed to be the Johnson-Nyquist. The purpose of the investigation is to identify the budget margin available for a realistic radar channel for future imaging applications. The image acquisition speed of $10\ Hz$ is the driving parameter. It emerges that adopting an array of 30×30 elements, and accounting for a $SNR_{min} = 20\ dB$ for a realistic quasi-optical channel, 100 points in the longitudinal direction can be scanned in real time while having a room of $23\ dB$ left for the design.**

***Index Terms*—SNR, PCA, radar, time-domain system.**

I. INTRODUCTION

So far, space science has been the only niche application that could afford the costs of the solid-state heterodyne up and down converters required to respectively generate and detect THz signals [1], devices that were used also to develop Radar systems for stand-off security applications [2, 3]. Complementary to these systems, photoconductive antennas (PCAs) have emerged as wide-band THz spectra generators/receivers for frequency and time domain sensing (FDS, TDS) architectures [4]. Recent breakthroughs [5-9] highlighted the potential of PCAs for being adopted as sources in radar like architectures designed to detect concealed weapons at stand-off distances.

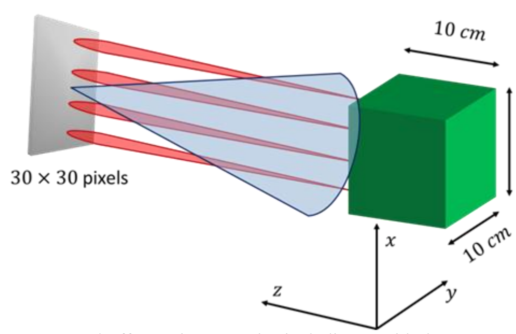

Fig. 1: A stand-off security scenario, including a wide beam transmitting source and an array of narrow beams receivers, focusing on the different spots of the target.

In this paper the SNR budget analysis of such a system is presented. A possible stand-off scenario is depicted in Fig.1. The target is a volume of sides $10cm \times 10cm \times 10cm$, which will be sampled in the three axes at a frame rate of $10\ Hz$. The lateral resolutions are associated to the number of pixels, whereas the vertical resolution, associated to a bandwidth of 300GHz, is $\delta_z = 2mm$. The strategy is to design a focal plane imaging array, composed of $N_x \times N_y = 30 \times 30$ pixels to reconstruct the lateral image, while the longitudinal (z) information will be encoded in the radar time of flight. To reconstruct the time of flight, a pulsed signal is transmitted and then received in N_z points.

II. Maximum SNR in Real Time Refresh Rate

In order to quantify the signal to noise properties of the system, independently from the properties of the channel, we analyse an ideal non-dispersive link. As a TX source of THz power we have available the recently developed PCA source of $P_{tx} = 1mW$ of average power, pulsed with a repetition rate of $f_L = 80\ MHz$, and period $T_L = f_L^{-1}$, with each i^{th} pulse arriving at the RX gap at time $t = t_i$, spread over a spectrum from 0.1 to $0.7\ THz$, as described in [7]. The adopted pulsed laser, characterized by a total power of $P_L^{tot} = 250\ mW$, is split in two different beams of $P_L^{TX} = P_L^{RX} = 125\ mW$, inducing the same photoconductivity transient both in transmission and reception, and has pulse width at half maximum of $\tau_L = 100\ fs$. The adopted photoconductive material is a low temperature grown (LT) Ga-As, with a carrier lifetime of $\tau_r = 0.3\ ps$.

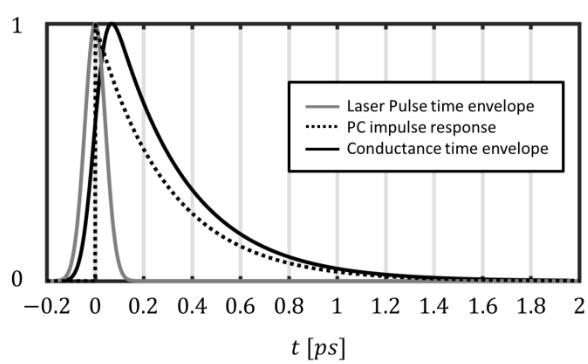

Fig. 2: Normalized time dependences of the laser pulse, the impulse response of the semi-conductor and the induced conductivity.

The incident optical pump injects a number of electrons in the semi-conducting gap of the antenna, which translates into a time dependent conductance transient $g(t)$, shown in Fig. 2 together with the time evolution of the incident laser pulse and of the LT GaAs impulse. At every cycle T_L, these carriers will be pushed by the TX field and accumulated across a capacitance every to reconstruct the incoming field. To generate a time trace with N_z points in the vertical direction of Fig.1, the TX signal is sampled N_z times. The time resolution, $\delta_t = \delta_z/(2c)$, is obtained changing the optical path of the laser with a chain of micrometrically tuneable mirrors.

The number of electrons accumulated during each laser pulse period across the antenna gap's capacitance is taken as the metric to estimate the performances of the PCA link:

$$SNR = \frac{N_{el}^{signal}}{N_{el}^{noise}}. \quad (1)$$

II.1) Maximum Number of Electrons from Signal and Noise

Assuming an impedance matching condition when the laser is present, the TX signal is entirely absorbed by the RX gap and transformed into electrostatic energy stored across the antenna capacitance. Each TX pulse contains an energy of $E_{pulse} = P_{ave}/f_L = 12.5\, pJ$. This effectively charges the capacitance of the gap (taken equal to $C = 1\, fF$) to a value $CV^2/2 = E_{pulse}$, corresponding to a number of electrons of $N_{el}^{pulse} \approx 10^6$. To obtain the SNR necessary to recover a point in the trace, a number of acquisitions, M_{acq}, has to be performed, resulting in a larger number of accumulated electrons: $N_{el}^{max} = M_{acq} \times N_{el}^{pulse}$. Note that the desired number of acquisition, M_{acq}, is limited by the desired image refresh rate, leading to: $N_{el}^{max} = \frac{T_{rf}}{T_L N_z} \times N_{el}^{pulse}$.

Regarding the thermal noise current, this can be expressed via its RMS value, with the well-known formula:

$$< i_n >= \sqrt{\frac{4kT}{R_{off}} BW_n}\,, \quad (2)$$

where $BW_n = T_{rf}^{-1} = 10\, Hz$ is the noise effective bandwidth of the system. This average noise current corresponds to a RMS noisy electrons generation rate of $< r_n >=< i_n > /e^- = N_{el}^{noise}$, where $e^- = 1.6 \cdot 10^{-19}\, C$ is the charge of an electron.

II.2) Maximum signal to noise ratio

In the present scenario, the generated source power is equally split over all the pixels of the receiving array, which leads to a reduction of the SNR of $\sqrt{N_x \times N_y}$. Moreover, the laser beam is also equally split over all the elements of the receiving array. Considering that the relation between the laser power and the induced conductivity amplitude is linear, the SNR is further reduced $\frac{N_x \times N_y}{D}$ times. As demonstrated in [7], $D = 25$ accounts for the fact that in order to have a good impedance match for the transmitting array, the optical power needed is 25 times less. Following all previous considerations, Equation (2) can now be expressed as:

$$SNR_{max} = \frac{N_{el}^{max}}{N_{el}^{noise}} \frac{D}{(N_x \times N_y)^{\frac{3}{2}}} \quad (3)$$

In Fig. 3 we show the dependence of the SNR_{max} in (3) on the number of z points analyzed for 900 receivers.

In a realistic design, with the object under analysis placed at a distance of $2\, m$ from the system, we need to account for a minimum $SNR_{min} = 20\, dB$ to allow for spreading and losses in the channel; yet, with this Signal to Noise Ratio we are able to reach values for N_z up to 100 points having quite some room, $23\, dB$, left for design purposes.

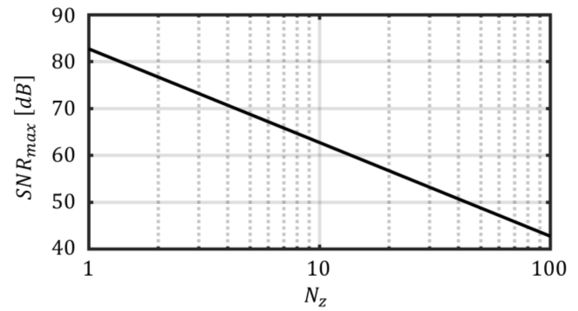

Fig. 3: Variation of the SNR_{max} as a function of the number of sampled points in z for a receiving array of 900 pixels, each one of them receiving the same source power $P_{r,i} = P_{tx}D/900$ and being excited by the same laser power $P_{L,i} = P_L^{rx}D/900$.

III. Conclusions

In this paper we presented the Signal to Noise Ratio analysis of a pulsed time-domain radar based on active photo-conductive antennas for stand-off imaging operating at real-time refresh rate. The system implements a focal plane array solution of 900 elements to split the power from the fs laser over all the pixels, which allows the acquisition of the THz image at a 10 Hz rate. After the noise analysis with the ideal link, it emerges that, to allow for the implementation of a realistic quasi-optical channel ($SNR_{min} = 20\, dB$), up to $N_z = 100$ points can be scanned in real time, achieving a resolution of $\delta_z = 0.2\, mm$; this also leaves a capacity of $23\, dB$ for design purposes. The actual antenna design, the channel design, the noise filtering and the validations will be presented at the conference.

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