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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 photoconductive-emitters have been developed, providing up to 1 mW of pulsed power in the range of frequencies between 0.1 and $0.7\,THz$. In this paper we study the potential use of such sources for future pulsed radar systems aiming at stand-off imaging applications. Specifically, we investigate the image frame rate and Signal to Noise Ratio budget that can be obtained using these photoconductive sources. It emerges that adopting a receiving array of $14 \times 14 \simeq 200$ elements, a 3D image with a Field of View (FoV) of $6cm \times 6cm \times 100cm$ and resolution of $4mm \times 4mm \times 1mm$ can be generated in $80Hz$ with a $SNR_{min} = 30\,dB$, including realistic quasi-optical channel efficiencies.**

I. INTRODUCTION

Photoconductive antennas (PCA's) have emerged as wide-band THz spectra generators/receivers for time domain sensing (TDS) architectures [1]. These systems consist of a transmitter and a receiver composed of PCA devices excited by ultrafast pulsed laser. The transmitter is biased to a constant level, that together with the optical illumination generates the current exciting the antenna system [2]. The field radiated by the transmitter, after investing and being scattered back by the object under analysis, impinges the receiver, excited by the delayed laser pulse; the delay is controlled by a chain of micro-metrically tunable mirrors [3]. Even though such systems were able to generate fields with spectral components up to $7\,THz$, the difficulty to generate power with PCA devices has always been the hurdle to overcome, demanding long integration times and thus rendering architectures adopting these sources adoptable only for niche applications. However, recent breakthroughs, [4], have proved able to increase the power radiated by pulsed PCA antennas up to the mW level. For this reason PCA's now emerge as suitable devices to adopt as sources in radar architectures for different purposes, depending on the operating frequency. The present paper introduce a possible radar architecture designed to detect concealed weapons at stand-off distances, along with the SNR budget of such a system. The imagined stand-off scenario is depicted in Fig.1.

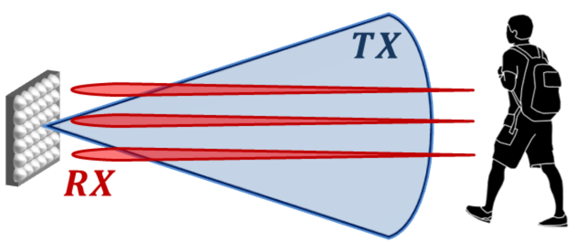

Fig. 1: A stand-off security scenario, including a wide beam transmitting source and an array of narrow beams receivers.

II. IMAGE RECONSTRUCTION

To reconstruct a 3D image, the field of view (FoV) will be divided in cuboids whose lateral dimension is defined by the system lateral resolution, δ_ρ; the lateral resolution is limited by the dimensions of the antenna in reception and the number of pixels, $N_x \times N_y$. As far as the longitudinal resolution, δ_z, is concerned, this is set by the bandwidth of the pulsed signal. The strategy is then to design a focal plane receiving array composed of $N_x \times N_y \simeq 200$ pixels to reconstruct the lateral FoV, while the longitudinal FoV information will be encoded in the radar time of flight.

The signal periodically radiated by the transmitter is acquired by the receiver using a stroboscopic sampling technique: adjusting the laser delay path by controlling the chain of mirrors, the receiver will gate one instant of the incoming field per radiated pulse, eventually creating a time trace of N_Z points. The time resolution of such a trace, $\delta_t = \delta_z/(2c)$, is directly related to the longitudinal resolution, is obtained by micro-metrically controlling the laser path toward the receiver. This time resolution, depending on the pulse width at half maximum of the radiated field is $\delta_t = 1.5\,ps$, giving a longitudinal spatial resolution of $\delta_z \simeq 1\,mm$.

Each element of the TX array radiates an energy $E_i^{TX} = 50\,fJ$, for a total radiated energy of $E_{tot}^{TX} = N_x \times N_y \times E_i^{TX} = 10pJ$ in each pulse. The system is pulsed at a repetition rate $T_L = 12.5\,ns$, with each radiated i^{th} pulse arriving at the gap of each receiving element spread over a spectrum from 0.1 to $0.4\,THz$. The energy radiated with every pulse by the transmitter, E_{tot}^{TX}, reaches each one of the receiver gaps after being scattered by the target under analysis. Being the target looked at by the receiver array architecture with $N_x \times N_y = 200$ lateral pixels, and distributing the source the radiated energy evenly into these pixels, a portion of $E_{tot}^{TX}/200$ is first scattered into a $\Omega_{bs} = 2\pi$ solid angle, and then received by each one of the array elements in reception, as showed in Fig. 2.

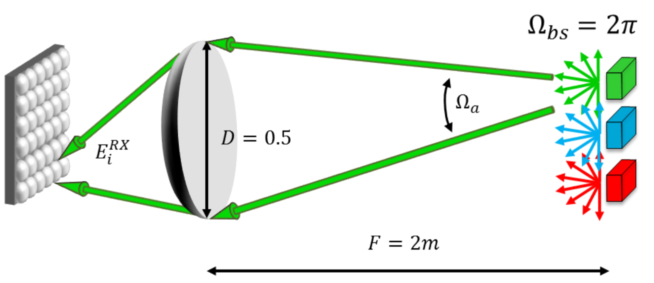

Fig. 2: receiving scenario, with a focusing lens of diameter $D = 0.5m$, positioned at $F = 2m$ from the target. The field radiated by the transmitting device is scattered back by the target into a solid angle $\Omega_{bs} = 2\pi$, and received by the each pixels into a Ω_a solid angle. Effectively, the target can be seen as composed of cubicles of size $\delta_\rho \times \delta_\rho \times \delta_z$.

The losses introduced by the path from the transmitter to the receiver are multiple. We take a target illumination efficiency by the TX device of $\eta_{ill} = 0.5$, and a reflection efficiency of $\eta_{refl} = 0.5$. Assuming then an antenna diameter of diameter $D = 0.5\,m$, positioned at $F = 2\,m$ from the target, each pixels receives the incoming field into a solid angle of Ω_a, with spill-over losses of $\eta_s = \Omega_a/\Omega_{bs} = 0.0074$. Accounting now for a receiving efficiency at each receiving gap of $\eta_{RX} = 0.5$, the total energy received per pixel per each pulse is given by:

$$E_i^{RX} = \frac{E_{tot}^{TX}}{N_x \times N_y} \eta_{ill}\, \eta_{refl}\, \eta_s\, \eta_{RX} = 0.05\,fJ \qquad (1)$$

Accounting for all the different loss mechanisms, one reaches a comprehensive quasi optical efficiency of $\eta_{QO} = -53\,dB$. Under the hypothesis of impedance matching condition for a $R_{gap} = 100\,\Omega$, with a pulse duration for each received signal of $\tau_p = 1\,ps$, we can estimate the voltage in each receiver gap to be:

$$v_i = \sqrt{\frac{E_i^{RX}}{\tau_p} R_{gap}} = 70\,mV \qquad (2)$$

The average voltage in each period T_L will be instead:

$$v_{gap} = v_i \frac{\tau_p}{T_L} = 60\,\mu V \qquad (3)$$

III. SNR AND FOV ENHANCEMENT

The SNR budget analysis of such a system is here addressed. The metric taken to estimate the performance of the PCA link is the signal to noise ratio of the system:

$$SNR = \frac{v_{gap}}{<s_{v,n}>\sqrt{BW_n}} = \frac{v_{gap}}{<v_n>} \qquad (4)$$

where v_{gap} is the average signal induced on each RX gap, $< s_{v,n} > = 7\,nV/\sqrt{Hz}$ is the Johnson noise voltage spectral density introduced by the amplifier, and $\sqrt{BW_n}$ its detection bandwidth. Imposing a minimum $SNR = 30dB$, it is apparent that, assuming that all the $N_x \times N_y = 200$ pixels can be read-out simultaneously, one point in the 3D FoV can be resolved in:

$$T_{acq} = \frac{1}{BW_n} \simeq 12\mu s \qquad (5)$$

In order to generate a $1\,m$ long longitudinal trace with a longitudinal resolution of $\delta_z = 1mm$, one needs to sample the signal in 1000 different time points. This operation collectively requires $T_{acq} \times 1000 = 12\,ms$.

The proposed 200 focal plane array (14×14) in Fig. 1 has a FoV of $6cm \times 6cm \times 100cm$, with lateral resolution $\delta_\rho = 4\,mm$ (for a $0.5\,m$ antenna and target at $2\,m$), and a potential frame rate of 80Hz. This FoV could be further increased by scanning the optical laser over several of these arrays sequentially. Virtually, a FoV of $60cm \times 60cm \times 100cm$ can be achieved at imaging speeds of roughly $1\,Hz$, using a single source of $1mW$ radiated power.

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