Ph.D. in Information Technology
Thesis Defense

July 6, 2022
at 11:00
Room Beta

Simone RICCARDO – XXXIV Cycle

Time-gated SPAD systems for visible and near-infrared photon counting

Supervisor: Prof. **Alberto Tosi**

Abstract:

Single-photon detectors are nowadays well consolidated devices, finding employment in a multidisciplinary spectrum of both scientific and industrial applications. They are exploited in material science and biology to measure fast fluorescence decays, in rangefinders to precisely timestamp laser return echo pulses, and have been applied to the quantum optics fields to enable quantum computing and quantum communications.

While originally designed as vacuum tube devices, the vast majority of single-photon detectors are today Single-Photon Avalanche Diodes (SPADs) and Superconducting Nanowire Single-Photon Detectors (SNSPDs). Even though SNSPDs can reach superior detection performance, they rely on superconducting material properties, hence require bulky cooling solutions to be operated at cryogenic temperatures. On the other hand, SPADs are compact and reliable devices that are fabricated with microelectronic technologies. Indeed, for the visible range and up to 1 µm wavelengths, silicon SPADs can be fabricated with standard CMOS processes, thus they can be monolithically integrated with dedicated electronics in large-format arrays. For detecting single photons beyond 1 µm, SPADs in different materials, like III-V compounds and germanium, can be easily bonded to Read-Out Integrated Circuits (ROICs) for developing highly compact detectors, thus making such technologies quite promising solutions for all photon counting application in the Short-Wave Infrared Range (SWIR). Beyond their ruggedness and overall good detection metrics, SPADs can be operated with moderate to none cooling solutions. Additionally, a rather unique SPADs' feature is their ability to be time-gated: they can be swiftly driven from OFF to ON condition in just few hundreds of picoseconds, thus paving the way to new single-photon counting techniques.

The goal of this Ph.D. work is to leverage SPADs' time-gating capabilities to develop: i) a 16 × 16 SPAD camera enabling video-rate Non-Line-Of-Sight (NLOS) imaging for the first time; ii) a pair of high-throughput detectors based on silicon and InGaAs/InP SPAD to be employed in free-space and fiber-coupled Quantum Key Distribution (QKD) applications.

This dissertation is divided into four chapters, which are organized as follows:

Chapter 1 deals with the concept of single-photon counting. The most relevant single-photon detectors are here reviewed, and their figures of merit highlighted. Among those, SPADs are selected as the most suitable devices for achieving the desired goals. Then, gated-mode operation is discussed as a technique to either perform a time-domain selection of the incoming photons, or to mitigate the detector's noise, or even to increase its dynamic range.

Chapter 2 and Chapter 3 present the design of a time-gated 16 × 16 SPAD camera developed within the DARPA "REVEAL" project. In particular, Chapter 2 describes the requirements of NLOS imaging and compares them with the features offered by existing state-of-the-art SPAD-based sensors. On the basis of such requirements, the development of a new fully-integrated 16 × 16 SPAD array is

presented from a microelectronics standpoint and all the related design choices are discussed. Chapter 3 deals with the integration of such sensor in the final camera system, whose goal is to interface the 16 × 16 SPAD array with an existing NLOS measurement setup, proving its scalability by making it faster and optimizing its size, weight, power and cost. Firstly, the developed hardware and software solutions are illustrated. A full characterization of the camera follows, and lastly some NLOS reconstructions are reported.
Chapter 4 describes the design of a SPAD-based system compatible with both silicon and InGaAs/InP SPADs to be embedded in a QKD receiver within the EC-funded "MeTISQ" project. Time-gating technique is here exploited to reduce the detector's dead time, hence make it reach state-of-the-art throughputs. The design of the employed architecture is guided by the solutions that are available in literature, and the newer design choices highlighted and targeted to guarantee high count rates and long-term stability. Lastly, system characterization is presented, and its performance assessed.

PhD Committee
Prof. **Massimo Ghioni**, DEIB-Politecnico di Milano
Prof. **Guido Masera**, Politecnico di Torino
Prof. **Lucio Pancheri**, Università di Trento