Ultra-high speed photodiodes for superconducting logic (LIGHTNING)

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ABSTRACT (100 words)

We envision future information society enabled by superconducting logic in core networks to switch and route data streams in optical communications network. For the vision we propose and develop a fiber optic connection to the rapid single flux quantum logic in order to tap into its potential and allow more than 100 times lower power consumption per logic operation than state-of-the-art electronics today. We have developed new type of 4 K high speed photodiode to enable down streaming of data to logic circuit. Proposed solution can be also used in classical supercomputers and quantum computers to solve their interface bottlenecks.

Keywords: superconducting logic, high data rate, supercomputer, quantum computer, quantum, photodiode

1. INTRODUCTION

The development of society as a whole is characterized by an ever-increasing need for more bandwidth, but meanwhile datacenters and networking constitute larger and larger part of CO_2 emissions. Already in 2016, data-centers produced 2 % of the global CO_2 emissions, matching that of the aviation industry [1]. 48 % of total power is consumed when transferring data from data centers to end user [2]. Disruptive new approaches are needed to enable sustainable development.

We envision future information society enabled by superconducting logic used in core networks to switch and route data streams in optical communications network. Until now, the efficient utilization of superconducting rapid single flux quantum (RSFQ) logic has been impeded by the difficulty in making the electrical interconnection from the RSFQ-chip to the external world because the RSFQ-chips operate in cryostats at 4 K temperature. We propose and develop a fiber optic connection to the RFSQ in order to tap into its potential and allow more than 100 times lower power consumption per logic operation (including power for cooling RSFQ to 4 K) than state-of-the-art electronics today. In the future, we expect that this technology will allow to build 100+ GHz optical links to RFSQ circuits but also to aid interfacing to classical supercomputers and quantum computers facing similar interface bottlenecks as RSFQ-logic.

In LIGHTNING, we have developed a new type of 4 K high speed photodiode to enable down streaming of data to a logic circuit. The photodiode is based on the so-called uni-traveling carrier photodiode (UTC-PD) concept utilizing high electron mobility shown to achieve bandwidths up to 340 GHz at room temperature [3]. However, the use of UTC-PDs at 4 K has been limited because of lower bandwidth associated to reduced electron mobility, and reduced efficiency at wavelength range around 1.55 µm used in core networks. Our development is based on a recent innovation of a new photodiode material system applicable to UTC-PDs. The main result of the project is development of proof-of-principle component and its semiconductor technology. Besides, we have addressed PD's optical and electrical interfaces. This development includes a new way to attach optical fiber to photodiode to achieve precise and robust optical connection at 4 K. Moreover, electrical testing is based on specifically designed RF circuits transmitting data from PD to electrical domain, and in future to RSFQ circuit. Current demonstration indicates that the PD concept works, and technology is viable.

2. STATE OF THE ART

Until now, the efficient utilization of RSFQ logic has been impeded by the difficulty in making the electrical interconnection from the RSFQ-chip to the external world because the RSFQ-chips operate in cryostats at 4 K temperature. When metallic wires are used to transmit electrical signals, the performance and complexity of the RSFQ circuits is limited by the thermal load from room temperature to 4 K through the wires. This problem can be solved by combining optical signal transfer with optical-to-electrical (OE) signal conversion at cryogenic temperatures. Moreover, RSFQ-circuits are very fast (200–300 GHz clock frequency), enabling low latencies in networking.

InGaAs pin photodiodes have been demonstrated with high responsivity and relatively high bandwidth at low temperatures for wavelengths around 1.3 µm [4], [5]. However, in core networks, where the data rate is the highest, 1.55 µm components are required but not available because of the bandgap shrinkage of InGaAs as a function of temperature. InGaAs UTC-PDs have recently gained tremendous success in THz communication due to their inherently fast modulation bandwidth. Unlike traditional pin-PDs, the UTC-PDs use only one carrier type, the electron, for transporting current, making them very fast. The fastest PDs are based on the UTC-PD design and reach 340 GHz bandwidth (- 3dB) and operate up to 900 GHz at room temperature [3]. Moreover, UTC-PDs operated at 4 K have been demonstrated [6] showing roughly one order of magnitude lower bandwidth compared to the best room temperature results. Low temperature bandwidth limitation originates from alloy disordering [7] induced by the fact that In and As are always somewhat randomly distributed in InGaAs crystal, causing scattering when electron waves propagate in semiconductor crystal.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

UTC-PDs developed in the LIGHTNING project enable building high speed optical receivers for 4 K temperature in core network based on operation around C-band (wavelength 1530–1565 nm), which corresponds to the amplification range of erbium doped fiber amplifiers (EDFA). EDFA is the enabling technology in long range optical communication. Moreover, we medicate bandwidth penalty associated with alloy disordering.

LIGHTNING project sets foundation for one key building block needed to enable RFSQ based data routing, but also other applications benefit from the developed technology. Our vision is that in phase 2 we will build a proof of principle router addressing the problem as a whole. Routers in 2018 reach more than 3 Tbits/s per instrument [8] (slot in rack) and double their capacity every 18 months, indicating that **routers with 300+ Tbits /s will be needed in 2028**. With an RSFQ element a single operation for each bit at this rate costs only about 30 µW (10^{-19} J/bit) of energy [9]. Even when taking into account the cooling power needed to cool the RSFQ circuit to 4 K it has been estimated that the energy efficiency of superconducting electronics will be at least a factor of hundred better than what is possible with high-speed semiconductor based systems [9]. The relative advantage is the higher the more complex the sequential data processing operations become. **RFSQ-logic supports society's need to scale the bandwidth for the next few decades** because of the extremely low power consumption per logic operation.

A cryogenic optical data-bus, which can feed data in classical superconducting computers, would be an important enabler for improved high-performance computing. As such it would contribute to advancement of a vast variety of applications in science and industry, such as Big Data analysis, discovery of new drugs, and design of new materials. Crucial for the mankind could be improved modelling of climate change to guide policy makers. This modelling will be based on enormous amounts of input data from sensors across the globe Moreover, an optical data-bus can feed data in quantum computers using single-flux-quantum coprocessor between photodiodes and qubits. The approach contributes to the introduction of quantum computers with their unique characteristics to benefit society.

4. PROJECT RESULTS

The prototype UTC-PD (schematic structure is shown in Fig. 1) consists of material layers specifically chosen so that absorption of the intended wavelengths at cryogenic temperatures is only taking place in the p-absorption layer. The other layers around the absorption layer have higher bandgaps that allows the target wavelengths to pass through. Electrons are diffused from the absorption layer to the n-collector layer, in which there is an electric field that quickly sweeps the carriers to the transparent contact layer. On the p-side there is also an electron diffusion blocking layer that effectively blocks the diffusion of electrons towards the p-contact.

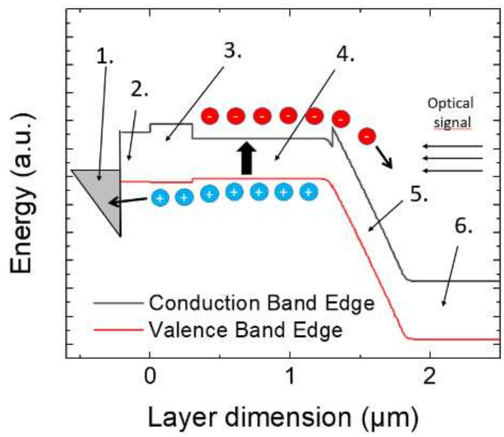

Fig. 1. Band diagram for novel UTC-PD design towards high performance low temperature PDs. Layers 1: p-metal, 2:transparent p-contact, 3: p- electron diffusion blocking layer, 4: p-absorption layer, 5: n- collector layer, 6: transparent contact layer. Interfacial layers, Fermi levels and carrier profiles omitted for simplicity.

The external quantum efficiency (EQE) measurements were done on the prototype UTC-PD component at room temperature. A NIST-calibrated germanium photodiode was used as a reference detector against which the response of UTC-PD was normalized. Fig. 2 shows the external quantum efficiency of the UTC-PD from 1200 nm to 1800 nm at bias voltages of 0 V and –5V. The results suggest that there is only very little shunt component at reverse bias as the curves are almost identical for both bias voltages. This means that any defects that could lead to shunt paths through the active area are absent. The EQE response also shows a clear peak at ~1750 nm which closely corresponds to the band-to-band transition of the p-absorption layer at room temperature. The EQE of the UTC-PD at the peak was about 20% at –5 V. which can be considered very good for the thin high-speed absorption layer used in this prototype.

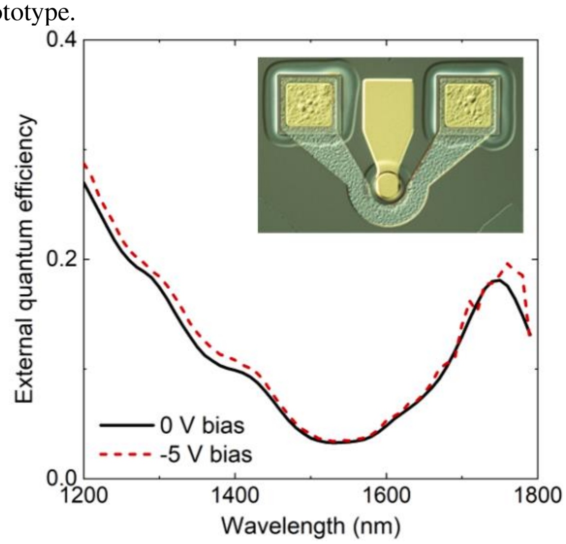

Fig. 2. Quantum efficiency of the UTC-PD at room temperature at bias voltages of 0 V and –5 V. Insert shows microscope image of a tested chip.

The photodiode chips will be bonded to transmission lines on silicon- or GaAs-based test substrates. A cryogenically compatible connector for aligning single mode optical fibers has been developed. The connector is assembled from pieces of silicon cut from silicon wafers and assembled using adhesive bonding in few steps. Shallow, 120 µm wide grooves are used align the optical fibers. The final desired fiber-to-photodiode distance can be set by controlling the position of the fiber along the fiber groove, before permanently adhering the fibers with epoxy. Both of the optical and electrical interfacing methods are compatible, in future, for silicon photonics integration. The use of mainly silicon as the structural material ensures low thermal deformation and compatibility with test substrates.

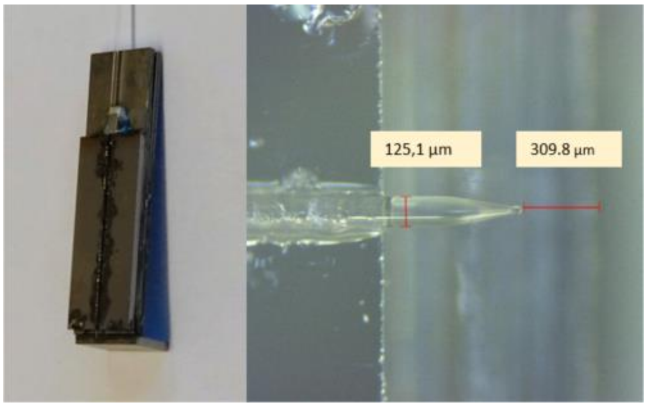

Fig. 3. Left: Image showing the assembled low temperature compatible optical connector that is mounted on top of the UTC-PD and attached to same carrier as PD. Right: Microscope image of the lensed fiber end, with measurements indicating the fiber diameter and offset distance to account for photodiode height. See Figure 4, detailing test complete test circuit.

Two different test platforms have been designed and fabricated for characterizing photodiodes. One consists of an undoped GaAs chip with Au coplanar waveguides (CPW) and bonding pads evaporated on it. The GaAs chip is mounted on a high-frequency printed circuit board (pcb) which contains a CPW matched to a 1.85 mm coaxial connector allowing direct measurement of the generated electrical signal with a 50 GHz oscilloscope. We are currently building optical assemblies on these test circuits in order to further validate PD-concept. A more advanced measurement, electro-optic sampling has also been designed on the platform which allows a non-contact measurement of the pulses with sub-ps time resolution up to hundreds of GHz bandwidth.

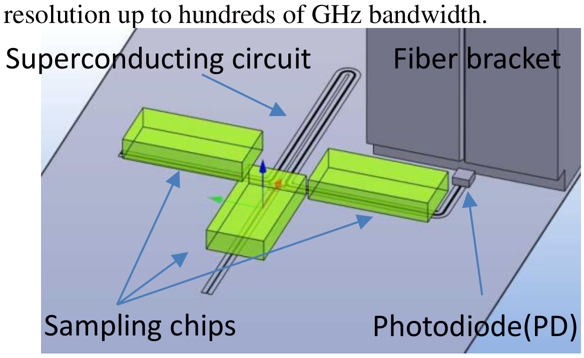

Fig 4. Integration concept showing fiber bracket from Fig. 3, UTC-PD, superconducting circuit and electro-optic sampling chips used for measuring pulse shapes.

With the final application of superconducting electronics (SE) in mind, a variety of superconducting Josephson junction arrays on silicon chips have been designed and fabricated. Measurements of voltage across Josephson junction arrays (JJAs) as a function of current pulse time integral will reveal if the flux transfer works properly in the SE circuits. Together with computer simulations, statistical analysis of the electrical pulses can be carried out as well. JJAs with so-called characteristic frequency of 57 GHz should allow testing operation with pulses at 10 ps interval from each other corresponding to 100 GHz pulse frequency.

5. FUTURE PROJECT VISION

The first part (18 months) of phase 2 will increase TRL level of downstream (optical-to-electrical, OE) technology and integrate it with wavelength division multiplexing (WDM). WDM enables efficiently utilizing bandwidth of the fiber up to multiple TBit/s per fiber. Moreover, in collaboration with another project, we will demonstrate upstream traffic (electrical-to-optical, EO) of data from the RSFQ to room temperature using a fiber optic link between logic circuit and external world. In the later part (Months 19-36), we **aim to demonstrate first ever RFSQ optical router and a waveform generator for a quantum processor.**

5.1. Technology Scaling

Technologies used in LIGHTNING are based on conventional micro- and nanofabrication and micro-assembly technology. Key technologies (III-V semiconductors, RFSQ circuits and silicon photonics, assembly) are available through foundry services. Availability of manufacturing allows to quickly scale business when cases are validated.

Attract phase 1 takes from idea to proof of principle in lab environment (TRL from 1 to 3). Phase 2 aims to advance TRL of the photodiode towards testing in relevant environment (TRL5) but also to demonstrate at system level (TRL6). During planning of phase 2 project and during the project we identify business cases that are applicable for developed vision. After the 2nd phase project, it is possible to start piloting the relevant products.

5.2. Project Synergies and Outreach

In the second phase, the consortium needs to be complemented with partners in Silicon Photonics (SiPh) and increase resources to RFSQ development. Demonstrators require both R&D organizations and companie(s) from the networking industry to define and fabricate networking related demonstrators.

Phase 2 project will contribute towards solving down streaming bottlenecks in both classical and quantum computing, for example. Therefore we seek both internal and external partners involved in these fields. Discussion with potential partners from other Attract projects are on-going.

Dissemination of the results is done with open access policy in leading scientific journals. Moreover, non-technical literature is produced to raise awareness of the topic in society. We will arrange technology workshop, jointly with other EU-funded project in order to bring together people from different fields of technology landscape around networking, computing and low temperature electronics photonics.

Introduction of superconducting logic to benefit society provides vast opportunities to generate IP at different areas of technology map. We have already been rewarded with a FET-Open project *aCryComm* to explore some aspects of optical interfacing to superconducting logic and quantum computers. Phase 2 takes advantage of the solutions developed in aCryComm in upstreaming data from RFSQ-circuit.

5.3. Technology application and demonstration cases

In phase 2 we plan to design and realize two separate demonstrators which we expect to attract wide interest and pave the way to commercialization steps. We believe these demonstrators to contribute to solving the great scientific and societal problems by advancing high-performance computing as exemplified earlier in Sec. 3. Optical control of superconducting electronics would be very valuable e.g. for European quantum (Quantum Flagship, e.g. project OpenSuperQ) and metrology (European Metrology Network on Quantum Technologies) communities.

In the first demonstrator we want to demo first ever RFSQ-circuit based optical router. It takes a 200 GHz multi-wavelength-channel optical bit pattern from room temperature to 4 K in a cryostat, and controlled by an RFSQ circuit back to room temperature in one of selected optical fibers. This routing demonstrator is visualized in Fig. 5. An optical fiber delivers the input data stream to an integrated package with SiPh-based WDM, EO converters, SFQ logic, OE converters and diagnostic circuits for verification of proper operation of individual elements.

A second demonstrator is a novel cryogenic waveform generator which can be used to generate control signals to qubits in a quantum processor. **We want to generate arbitrary voltage waveforms at tens of GHz** with ultimate signal purity using a patent-pending technology. With the possibility to integrate a matrix of UTC-PD OE converters, and Josephson junctions to quantize voltage waveforms close to the quantum processor seems to be the ultimate solution to the requirement of least noisy control and error correction signals for qubits.

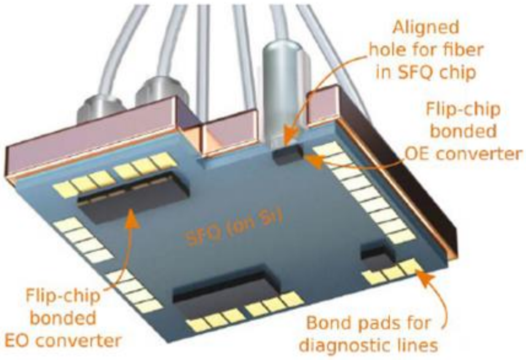

Fig 5. Image showing phase 2 integration concept between various elements.

5.4. Technology commercialization

Phase 2 enables a tangible demonstration of benefits of clearly defined technology packages to be exploited by private sector. Exploitable results are formed at a building block level (circuits, detectors, sources, assembly processes) and at a system level (routers, waveform generators, voltage standards, quantum computers…). This enables many opportunities. Project partners are already having multiple joint or separate efforts to protect IP around key topics.

5.5. Envisioned risks

Key technology risks are associated to development of different building blocks needed for demonstration. For this reason, we design also demonstrators with limited function that could be used to circumvent some of the potentially missing building blocks. Moreover, we co-operate with other projects that can deliver alternative building blocks.

5.6. Liaison with Student Teams and Socio-Economic Study

Project partners have a strong track record in supporting both MSc students and PhD students in their studies and thesis work. For collaboration with MSc level teams, we offer case studies in design and simulation of simple but relevant superconducting logic circuits. This is a rather unique opportunity as such topic is not common in any curriculum.

We will contribute to the ATTRACT socio-economic study by providing access to knowledge-pool of team leaders of the phase 2 consortium consisting of world class experts in different state-of-the-art technology research topics. Contribution can be arranged through interviews, participation to workshops and panel discussion or through written report.

6. ACKNOWLEDGEMENT

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