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Metamaterial-Graphene Photodetector for High-Speed Cryogenic Signal Generation

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Abstract Emerging cryogenic technologies suffer from scaling discrepancies due to limitations of electrical signal lines. Here we demonstrate a metamaterial-graphene photodetector able to generate high-speed electrical signals in a cryostat without any need for electrical feed lines. The concept is demonstrated by 112Gbps cryogenic optical communication. ©2023 The Author(s)

Introduction

Highest-capacity optical links are enabled by the continued development of high-speed photodetectors and modulators. With the emerging field of quantum computers, these devices might also be beneficial as high-speed and low thermal conduction links between room temperature (RT) and the cryogenic world[1].

Currently, cryogenic computing technologies rely on arrays of electrical coaxial radio frequency (RF) cables to connect to RT instrumentation. As good electrical conductors are also good thermal conductors, a high thermal exchange between the RT and cryogenic environment is inherent. Therefore, current systems suffer from scaling limitation due to finite cooling power and furthermore also by the practical implementations of more RF lines. Replacing these interconnects with optical fibers could drastically reduce the thermal exchange, reduce power consumption and furthermore also increase the bandwidth[2]. Therefore, photodetectors and modulators operating at cryogenic temperatures could drastically change cryogenic dilution refrigerator systems.

Electro-optic (EO) modulators offer at RT bandwidths of 110 GHz with photonic approaches[3], [4], and even beyond 500 GHz with plasmonic approaches[5]. Cryogenic operation of both integration schemes have also been demonstrated, showing the successful transmission of data out of a cryostat[6]–[8].

RT Photodetectors (PD) in the optical communication bands have been able to exceed 100s of GHz in operation speed with conventional technologies such as germanium[9] and the InP-platform[10], [11]. Recently, a plasmonic approach using graphene as active material was able to exceed 500 GHz in bandwidth[12].

Beyond telecommunication wavelengths, it is typical in narrow band gap semiconductor PDs to test cooled performance[13]. However, thus far there is very limited prior art that discusses the operation of telecommunication PDs in the few Kelvin regime – especially with respect to their frequency response and their use to form optical cryogenic data links[14].

In this paper we demonstrate the cryogenic high-speed operation of a metamaterial-graphene photodetector down to a few Kelvin. We reveal not only that the frequency response remains flat beyond 110 GHz with cooling, but also find an increase in received RF power of >10 dB. The device can further be operated fully passively, i.e., it does not rely on any electrical biasing linked to RT electrical lines. By this, it is essentially possible to have a cryogenic high-speed electrical source which receives its signal through a low heat carrying optical fiber. We further demonstrate this by showing a cryogenic communication link, where we encode a signal on an optical carrier using a plasmonic modulator at room temperature. The signal is then detected by the metamaterial-graphene PD at 4 K showing data transmission of 112 Gbaud PM-2, 40 Gbaud PM-4 and 16 Gbaud PM-8. These are, to the best of our knowledge, the highest data rates ever received in a cryogenic environment. The presented metamaterial-graphene PD is thereby an ideal candidate for scaling of future cryogenic super- and quantum computer applications, as it operates without any bias circuitry, offers highest speeds and does not suffer from carrier freeze-out.

Fig. 1: Cryogenic high-speed electrical source: Metamaterial-graphene photodetector. A schematic of the target to transfer an RF signal into the cryogenic environment via modulation onto an optical carrier is shown. The blow up visualizes the architecture of the graphene PD.
Concept and Room Temperature Operation

The goal of this work is schematically visualized in Fig. 1. An RF signal generated at RT is to be transferred to the cryogenic environment through an optical link without any electrical control lines into the cooled environment. A metamaterial-graphene PD placed inside the cryostat is used to receive the optical signal and return the RF signal directly within the cryogenic environment.

The metamaterial-graphene PD is visualized in Fig. 1. A monolayer of CVD grown and transferred graphene is integrated in a metamaterial perfect absorber (MPA) architecture[15], where the resonators are interconnected with contact lines. The structure allows for resonant optical absorption enhancement, where the perpendicularly oriented dipole resonators allow for polarization independent enhancement. Carrier extraction is enabled by the use of alternating contact metals which induce a p-n doping in the graphene channel. A more detailed discussion on the devices is provided in ref [12].

We first test the device for its capability to receive RF signals at room temperature. For this, we use a laser beating scheme to optically excite the PD and detect the electrical tone with an electrical spectrum analyser, see Fig. 2(a). We subtract any RF losses introduced by the probes and RF cabling to find the response of the PD. The normalized frequency response shown in Fig. 2(b) shows a flat frequency response with no roll-off in the measurement range from 3 to 110 GHz. The device is not electrically biased or gated and thereby is operated in a passive manner without the need for external control signals.

The measurement frequencies here are limited by the RF lines of the cryostat, but devices on the same chip have been shown to enable frequency bandwidths in excess of 500 GHz[12]. This device was specifically chosen as the operation with 0 V source-drain bias voltage and 0 V gate voltage leads to an almost optimum performance in terms of response.

Cryogenic Cooled Performance

We next investigate the influence of cooling on the device performance. We repeat the same bandwidth measurements as in RT presented in Fig. 2(b) for three distinct temperature regimes. (1) -40°C mimicking the range where thermoelectric cooling (TEC) is achievable. (2) 77K, the boiling point of liquid nitrogen and (3) 4K, the boiling point of liquid helium. The results are presented in Fig. 3. We find that the frequency response does not show a roll-off behaviour and observe an overall gain in response. As a comparison to RT, we choose the 30 GHz point and find (a) 3.5 dB gain at -40°C, (b) 4 dB gain at 77K and (c) 12.5 dB gain at 4K. We attribute this gain to an increase in the graphene carrier mobilities and reduced optical and electrical losses. Merely the 77K operation shows a non-flat response with a drop in the 10s of GHz range which recovers again at higher frequencies. We assume this effect arises from competing photodetection mechanisms within the device that have different frequency and temperature dependences. However, a more detailed study with more temperature levels and operation conditions is required to thoroughly understand this behaviour.

Fig. 2: Room temperature characterization of the metamaterial-graphene PD. (a) Schematic simplified laser beating characterization setup. (b) Normalized RF response of the metamaterial-graphene PD.

Fig. 3: Frequency response of the metamaterial-graphene PD as a function of temperature. (a) Normalized RF response measured at -40°C, revealing a 3.5 dB gain over room temperature. (b) Response at 77 K and finally the response at 4 K (c) showing a flat frequency response up to 110 GHz with a gain of 12.5 dB in comparison to the uncooled operation.
The metamaterial-graphene PD is therefore not only able to show high-speed operation down to liquid helium temperatures but retains these properties with a fully electrical passive operation \((V_0 = V_r = 0 \text{ V})\) and even has an improved response.

**Cryogenic Data Link**

To test the cooled metamaterial-graphene PD for its capability to be used for cryogenic high-speed signal generation, we test the data reception of the PD in a communication link.

We use a setup as schematically depicted in Fig. 4(a). A plasmonic Mach-Zehnder modulator\([16]\) is used to encode the random bit sequence onto an optical carrier. We use a 256 GSa/s arbitrary waveform generator (AWG) and an RF pre-amplifier to generate the electrical signal. The optical signal is then boosted by an erbium-doped fiber amplifier (EDFA), passed through a bandpass filter and sent into the cryostat in an optical fiber. The signal detected by the metamaterial-graphene PD is extracted from the cryostat with RF probes and cabling. At RT, the signal is amplified and received by a digital sampling oscilloscope (DSO). Lastly, the signal is retrieved by offline digital signal processing (DSP) including Timing Recovery, a least-mean square equalizer followed by a maximum likelihood sequence estimation, as well as a second least-mean square equalizer followed by the symbol decision.

The results in the form of eye diagrams for different modulation formats are presented in Fig. 4(b-d). After DSP, we achieve transmission below the SD-FEC with (b) PAM-2 signals at 112 Gbps with a bit-error ratio (BER) of \(2.93 \times 10^{-2}\) and (c) PAM-4 signals at 80 Gbps with a BER of \(3.91 \times 10^{-2}\). For higher modulation formats, we achieve (d) 64 Gbps with PAM-8 and a resulting BER of \(3.3 \times 10^{-2}\).

These data rates are limited by the lossy RF link out of the cryostat back to the RT signal detection. We measured a 30 GHz 3 dB bandwidth of the RF link strongly decreasing the generated signal of the PD. Making use of the signal directly within the cryogenic environment would result in much better signal-to-noise ratios, allowing for higher data rates.

**Conclusion**

We demonstrated a high-speed, beyond 110 GHz cryogenic photodetector based on a metamaterial-graphene architecture. The photodetector can be operated without any electrical biasing, essentially creating an in-cryogenic high speed RF source driven by optical signals. To the best of our knowledge, these are the fastest operated PDs at cryogenic temperatures.

Such compact and substrate independent devices could benefit high-speed superconducting and quantum computers by offering room temperature to cryogenic interconnects with low thermal exchange, reduced power consumption and high bandwidths potentially beyond 500 GHz. The work thereby has the prospective to solve the scaling bottleneck of these systems.

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Fig. 4: Cryogenic data transmission link. (a) Schematic of the setup with the metamaterial-graphene PD in the cryostat at 4K. (b-d) Resulting eye diagrams after offline DSP with data rates and bit error ratios. (b) PAM-2, (c) PAM-4, (d) PAM-8.
References


