High-Speed Pulsation of a Cryogenically Operable Bipolar Photodiode Module for the Josephson Arbitrary Waveform Synthesizer

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Karlsen, B., Bardalen, E., Nissilä, J., Fordell, T., Kieler, O., Palafox, L., ... & Ohlckers, P. (2020). High-Speed Pulsation of a Cryogenically Operable Bipolar Photodiode Module for the Josephson Arbitrary Waveform Synthesizer. In 2020 Conference on Precision Electromagnetic Measurements (CPEM). https://doi.org/10.1109/CPEM49742.2020.9191751

Publisher's version: DOI: 10.1109/CPEM49742.2020.9191751

High-Speed Pulsation of a Cryogenically Operable Bipolar Photodiode Module for the Josephson Arbitrary Waveform Synthesizer

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***Abstract*—This paper describes the development and testing of a prototype of a cryogenically operable bipolar photodiode module. Optical pulsation systems based on both a Mach-Zehnder modulator and a mode-locked laser have been used to measure the response of various samples, while immersed in liquid helium. Pulse widths down to 37 ps have been measured. By modifying the Mach-Zehnder-based system, a bipolar electrical pulse train has also been demonstrated from the module.**

***Index Terms*—High-speed electronics, Josephson junction, laser applications, optical modulation, pulse width modulation, pump laser, signal sampling, signal synthesis**

I. INTRODUCTION

For more than two decades, several National Metrology Institutes (NMIs) have been working on pulse-driven Josephson junctions arrays (JJAs) to synthesize quantum-accurate voltage waveforms. One promising approach to increase the amplitude and frequency of the synthesized waveforms is to use an optical input for photodiode modules, which have been custom packaged for a cryogenic environment [**?**]. These modules are operated in liquid helium [**?**], in close proximity to the JJAs that they bias with pulses. This method has already been used to synthesize unipolar waveforms from arrays of up to 3000 junctions [**?**].

This paper describes the development of a cryogenically operable bipolar photodiode module, and testing of it as a possible source for a pulse-driven JJA. The manufacturing follows the technique described in [**?**], and the modules are laid out to produce three-level current outputs.

II. THE BIPOLAR PHOTODIODE MODULE

The schematic and photograph of the module are shown to the left and right in Fig. 1, respectively. The module consists of two parallel-coupled InGaAs photodiodes, that were flip-chip bonded to a silicon chip-carrier, and reverse-biased by 5 V. The photodiode used is the Albis PD20X1, which has a 28 Gbit/s bandwidth and an integrated 100 μm diameter backside-lens to allow us a larger tolerance in the optical alignment [**?**]. The photodiodes were spaced by 4.5 mm to fit the optical connection to ferrule-ended fibers put through a borosilicate glass tube glued to the chip-carrier.

For pulse widths of a few tens of picoseconds, the signal wavelength is comparable to the track-length between the photodiodes. For unmatched impedance, this merging of the electrical signal-paths can lead to reflections. To counteract ringing, 50 Ω on-chip terminations were added in some of the samples, although this reduces the output power by 50 %.

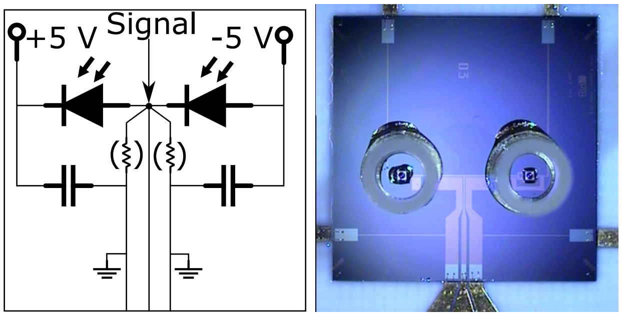

Fig. 1. Schematic (left) of the bipolar photodiode module. The electrical pulses from the photodiodes are merged in the T-cross point, with two parallel in-grown 100 Ω resistors to each ground strip in the on-chip terminated version. The photograph (right) of the module shows the photodiodes centered inside the borosilicate glass sleeves used to make the optical connection to ferrule-ended optical fibers.

III. EXPERIMENTAL SETUPS

Two laser pulsation schemes have been used to test these prototypes. For the measurements performed at PTB, a Mach-Zehnder modulator (MZM) (iXblue MX1300-LN-20), with a modulator driver (iXblue DR-DG20-MO) was used to directly modulate a continuous wave laser into a pulse code provided by a pulse-pattern generator (PPG). By this approach, the width of the laser pulses are related to the clock frequency of the PPG. The photodiode modules were immersed into liquid helium using a cryoprobe with two FC-to-ferrule fibers (one for each photodiode in the module) as input and a coaxial cable with SMA-connectors (subminiature version A) as output. The current pulses produced by the photodiodes were measured by a sampling oscilloscope with a 50 GHz bandwidth.

For the measurements performed at VTT, a fast mode-locked laser (MLL) [**?**] was used to produce a constant train of narrow pulses (15 ps full-width-half-maximum), and pulse density according to an input clock. The photodiode modules were immersed into liquid helium using a cryoprobe similar to the one used at PTB. The current pulses produced by the photodiodes were measured by a sampling oscilloscope with

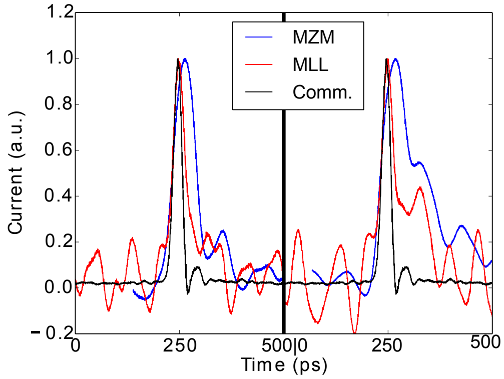

Fig. 2. Sampled waveforms for the positively-coupled photodiodes (immersed in liquid helium) in the samples with (left) and without (right) $50\ \Omega$ on-chip termination. The measurements from the MZM-based system (labeled MZM) are shown in blue, and the measurements from the MLL-based system (labeled MLL) are shown in red. The reference measurement of the commercially-packaged module at room temperature (labeled Comm.) has been added in both graphs and is shown in black.

a 20 GHz bandwidth. This system was also used to make reference measurements of the standard-packaged version of the same photodiode at room temperature.

IV. MEASUREMENTS

For the measurements with the MZM-based pulsations, the PPG was set to produce 0.94 gigapulse-per-second. The resulting optical pulses were applied to each of the photodiodes, separately, and for both the version with and without on-chip termination. The same was done for the MLL-based system, where the laser was set to produce a constant pulse train of 2.3 gigapulses-per-second. The resulting measured waveforms from the photodiodes in liquid helium are shown together in Fig. 2. As a reference, the measurement from the standard-packaged photodiode at room temperature is also added to the graphs in Fig. 2. From the measurements of both samples, it can be seen that narrower pulses are obtained from the photodiodes when the MLL is used as source. For the versions with on-chip termination, the MLL-based system produced a 37 ps pulse, whereas the MZM-based system produced a 62 ps pulse. It can also be seen that there is less ringing in the sample with on-chip termination. However, optimizing is needed to reduce the ringing to be comparable to that of the commercially-packaged module.

To demonstrate simultaneous bipolar operation, the output from the MZM-based system was put through an optical splitter. The first output was led directly to the cryoprobe input for the positively coupled photodiode, whereas the second output was led via an extra 2 meters of fiber, delaying this signal by about 10 ns. By setting the PPG to produce 62.5 megapulse-per-second, two consecutive optical pulses are produced 16 ns apart. Following this setup, the photodiode module puts out the waveform shown in Fig. 3, where two consecutive pulses of the same polarity come 16 ns apart, and the negative pulse comes 10 ns after the corresponding positive pulse.

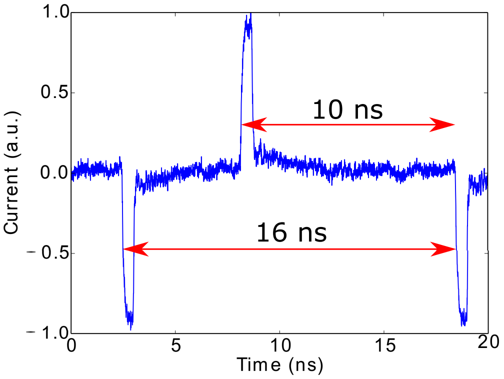

Fig. 3. Sampled waveforms for bipolar operation of the module without on-chip termination, in liquid helium. The figure shows alternating pulses, where two consecutive pulses of the same polarity come 16 ns apart, and the negative pulse is delayed by 10 ns with respect to the corresponding positive pulse.

V. CONCLUSION

We have developed a cryogenically operable bipolar photodiode module, and we have manufactured versions both with and without $50\ \Omega$ on-chip termination in order to investigate reflections in the transmission lines. These samples have been immersed into liquid helium and operated with fast laser pulses from two systems using a Mach-Zehnder modulator and a mode-locked laser. The resulting current waveforms have been measured with high-speed sampling oscilloscopes to pulse widths of 62 ps and 37 ps from the two systems, respectively. Bipolar operation of a module in liquid helium has also been demonstrated.

ACKNOWLEDGMENT

This project received funding from the European Metrology Programme for Innovation and Research (EMPIR) co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation program.

This research received funding from the Norwegian Research Council via the program Public Sector PhD and Academy of Finland.

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