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Optical pulse-drive and on-chip power splitter for the pulse-driven AC Josephson Voltage Standard

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***Abstract*—The pulse-driven Josephson Voltage Standard, also called Josephson Arbitrary Waveform Synthesizer (JAWS) is already well established for different applications in AC voltage metrology. To further increase the output voltage towards 10 V and to reduce the complexity of the JAWS systems we investigated two different approaches, which finally can be combined. One approach is to integrate an optimized on-chip power splitter to reduce the number of high-frequency (HF) channels from room temperature down to 4 K. A pulse pattern generator with less HF outputs will directly reduce the complexity and costs of a JAWS system. The second approach is to use an optical pulse-drive implementing cold photodiodes close to the JAWS chip. The use of optical fiber will have two main advantages: the optical fibers will reduce the high frequency noise and will enable an easy splitting into parallel optical channels. We will present first results with both approaches.**

Keywords*— Josephson voltage standard, Josephson arbitrary waveform synthesizer, SNS Josephson junction, optical pulse-drive, on-chip power splitter

I. INTRODUCTION

The pulse-driven AC Josephson Voltage Standard was first realized by NIST [1] and recent developments increased the effective output voltages up to 3 V [2]. This Voltage Standard is often called “Josephson Arbitrary Waveform Synthesizer” (JAWS), because DC and arbitrary AC voltages can be synthesized. The PTB Standard is based on SNS (S…superconductor, N…normal metal) Josephson junctions with Nb_xSi_{1-x} as barrier material [3]. For this application the Josephson junction series array is embedded in a HF transmission line (coplanar waveguide) to guarantee a homogeneous propagation of the GHz pulses. At the Josephson junctions these short current pulses are directly converted into flux pulses $\Phi_0 = h/2e$ (h is Planck’s constant and e the elementary charge). According to the Josephson equation, a time-dependent voltage is generated, which is quantized at all times. The signal-voltage is well defined by equation (1):

$$V_{signal} = A_{\Sigma\Delta} \cdot n \cdot m \cdot \Phi_0 \cdot f_{clock} \tag{1}$$

The output voltage V_{signal} is the product of the Shapiro-step number n (typical: n = 1), the number of junctions in the series array m, the flux quanta Φ_0, the sigma-delta digital pulse code amplitude $A_{\Sigma\Delta}$ ($0 < A_{\Sigma\Delta} < 1$, i.e. density of pulses in the code) and the clock-frequency f_{clock}. The maximum pulse-repetition frequency used for our JAWS is 15 GHz, limited by the maximum clock frequency of the pulse pattern generator (PPG).

Large arrays of up to 5-stacked SNS junctions have been implemented at PTB, with up to 30,000 Josephson junctions per chip (2 arrays @ 1 chip) [4]. The parallel operation of up to 16 arrays (on 8 chips) with 162,000 junctions in series was demonstrated to achieve an effective RMS output voltage of 2.25 V [4].

To further increase the output voltage and/or to reduce the complexity/costs of the JAWS setup, it is necessary to achieve large output voltages with less electrical pulse-channels at room temperature. In the following two sections we describe

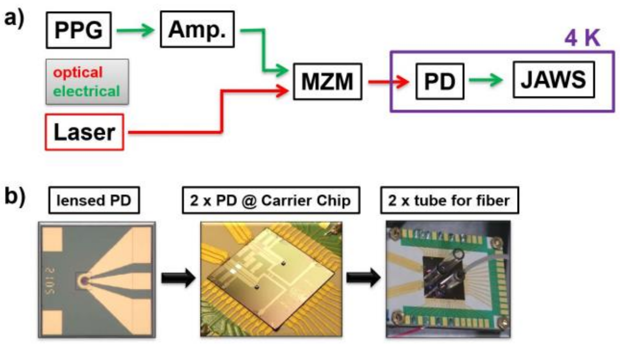

Fig. 1. a) Schematics of the optical pulse-drive setup. b) Photographs of the photodiodes and assembly on carrier chip with optical fiber.

the first results with an optical pulse-drive and two different versions of an on-chip power splitter.

II. Optical Pulse Drive

One approach for improving the JAWS setup is the use of an optical pulse-drive as suggested in [5] and further investigated in [6]. The use of an optical drive with high-speed photodiodes (PDs) operated at 4 K close to the JAWS chip could improve the JAWS in several ways. By using small bare photodiodes, the integration density of photodiodes at a carrier chip (or in a final development stage directly on the JAWS chip) can be fairly high to realize a cost-efficient parallel operation. Additionally, the use of optical fibers, instead of high-frequency coaxial cables, will reduce the thermal load, which is an important aspect for operating JAWS systems in closed-cycle cryocoolers. Furthermore, these fibers are removing the coupling noise introduced by the PPG and are also reducing the crosstalk inside of the cryoprobe. This might improve the overall JAWS performance at signal frequencies well above 1 MHz. By establishing a setup, where the PDs are in close vicinity to the JAWS array, the distortion and attenuation of the pulses will be reduced. Thus, the operation margins will be increased.

We developed an optical pulse-drive for the JAWS using high-speed photodiodes operated at 4 K, close to the JAWS chip. Optical fibers transmit the optical pulses to the lensed photodiodes, which are mounted by flip-chip technique to a custom-made silicon-carrier chip [7]. Fig. 1a) shows the schematics of the experimental setup. The pulse pattern is provided by the PPG. The amplified pulses are electrically transferred to a Mach-Zehnder Modulator (MZM). The MZM is coupled to a 1310 nm Fabry-Perot Laser. The optical pulses are transferred to the PD at 4 K by optical fibers. Fig. 1b) shows the PD (Albis PD20X1), which is suitable for high data rates up to 28 Gbit/s (left picture). The PD has an integrated backside lens and is mounted by flip-chip technology to a custom-made silicon-based carrier chip (center picture). This carrier chip uses superconducting HF-lines to guide the electrical pulses to the JAWS chip. DC-blocks and PD bias pads are implemented too. To mount the optical fibers glass tubes are glued to the carrier chip centered to the PD (right picture). The ferrule-ended fiber with a diameter of 1.8 mm can easily plugged into this tube. The flip-chip technology and

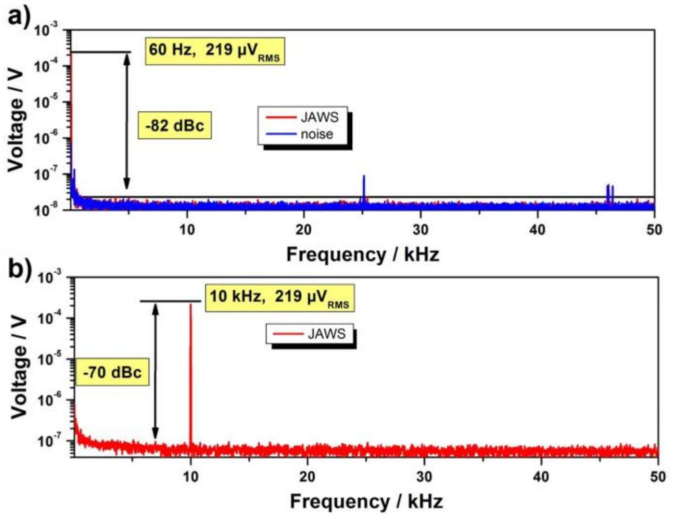

Fig. 2. a) Frequency spectrum of a sinusoidal waveform with a signal frequency of 60 Hz. b) Frequency spectrum of a sinusoidal waveform with a signal frequency of 10 kHz. For both signals the optical pulse-drive was used for a JAWS array with 100 junctions (f_{clock} = 15 GHz, $A_{\Sigma\Delta}$ = 0.2).

performance of the PDs at 4 K are investigated in detail in [7] and [8], respectively.

Unipolar sinusoidal waveforms were synthesized with a JAWS array of 3000 junctions and an output voltage of 6.6 mV RMS at a clock frequency of 15 GHz [9]. Using an array with 100 junctions only, sinusoidal waveforms were demonstrated in a frequency range from 60 Hz to 10 kHz, which is shown in Fig. 2. The PD were operated at the full speed of 15 GHz clock-rate.

III. On-Chip Power Splitter

Another approach to reduce the number of electrical pulse-channels at room temperature was realized by implementing on-chip power splitter as part of the JAWS chip [10], [11]. At PTB we investigated and realized two different types of splitters: a traditional one-stage Wilkinson power divider and a two-stage CPW-CPS splitter (CPW: coplanar waveguide, CPS: coplanar stripline) to split one pulse channel into two respectively four parallel JAWS arrays [12]. The power dividers were optimized using CST microwave studio simulations. For the Wilkinson splitter we realized an insertion loss of about 3 dB and a return loss of > 10 dB up to 25 GHz. For the CPW-CPS splitter an insertion loss of about 6 dB and a

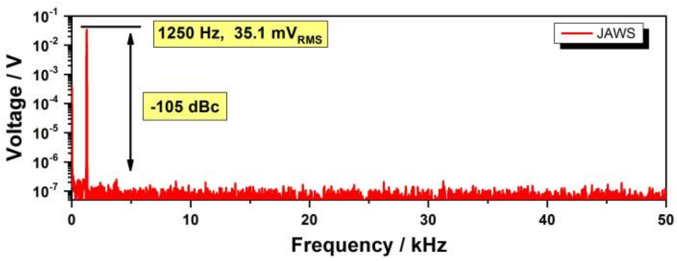

Fig. 3. Frequency spectrum of a sinusoidal waveform with a signal frequency of 1250 Hz and a signal amplitude of 35.1 mV RMS. A Wilkinson splitter was used to drive two JAWS arrays with 1,500 junctions each (f_{clock} = 10 GHz, $A_{\Sigma\Delta}$ = 0.8).

return loss of > 20 dB up to 30 GHz. Both splitters show an amplitude balance of below 0.3 dB.

Pure bipolar sinusoidal waveforms were synthesized with both splitter types, e.g. with the Wilkinson splitter we achieved 35.1 mV RMS at a clock-frequency of 10 GHz and a sigma-delta code amplitude of 0.8 using an array of 3000 Josephson junctions as shown in Fig. 3.

IV. Conclusions

In this work we presented an optical pulse-drive for the JAWS with PD operated at 4 K close to the JAWS array. First results with pure unipolar waveforms were achieved.

By implementing two types of on-chip power splitter we were able to reduce the number of electrical pulse-channels at room temperature. A two-stage CPW-CPS splitter and one-stage Wilkinson were optimized by CST simulations. First results were presented with pure bipolar waveforms up to 35 mV RMS using a JAWS array with up to 3000 junctions.

These results are promising achievements for increasing the output voltage of the JAWS.

References

[1] S. P. Benz and C. A. Hamilton, “A pulse-driven programmable Josephson voltage standard,” Appl. Phys. Lett., vol. 68, pp. 3171-3173, May 1996.

[2] N. E. Flowers-Jacobs, A. Rüfenacht, A. E. Fox, S. B. Waltman, J. A. Brevik, P. D. Dresselhaus, and S. P. Benz, “Three volt pulse-driven Josephson arbitrary waveform synthesizer;”, in Proc. CPEM 2018 Digest., Paris, France, July 2018, DOI: 10.1109/CPEM.2018.8501053.

[3] O. Kieler, R. Behr, R. Wendisch, S. Bauer, L. Palafox, and J. Kohlmann, “Towards a 1 V Josephson arbitrary waveform synthesizer,“ IEEE Trans. Appl. Supercond., vol. 25, pp. 1400305, 2015.

[4] O. Kieler, R. Behr, R. Wendisch, and J. Kohlmann, “Arrays of stacked SNS Josephson junctions for pulse-driven Josephson voltage standards“, EUCAS 2017, 13th European Conference on Applied Superconductivity, Geneva, 17-21 September, 2017, Switzerland.

[5] J. Williams, T. J. B. M. Janssen, L. Palafox, D. A. Humphreys, R. Behr, J. Kohlmann and F. Müller, “The simulation and measurement of the response of Josephson junctions to optoelectronically generated short pulses”, Supercond. Sci. Technol. 17, 2004, doi.org/10.1088/0953-2048/17/6/014.

[6] C. Urano, M. Maruyama, N. Kaneko, H. Yamamori, A. Shoji, M. Maezawa, Y. Hashimoto, H. Suzuki, S. Nagasawa, T. Satoh, M. Hidaka, and S. Kiryu, “Operation of a Josephson arbitrary waveform synthesizer with optical data input”, Supercond. Sci. Technol. 22, 2009, doi.org/10.1088/0953-2048/22/11/114012.

[7] E. Bardalen, H. Malmbekk, M. N. Akram, and P. Ohlckers “Reliability study of fiber-coupled photodiode module for operation at 4 K”, Microelectronics Reliability Journal 81, 2018, doi.org/10.1016/j.microrel.2017.10.034.

[8] B. Karlsen, O. Kieler, R. Behr, T. Nguyen, H. Malmbekk, M. Akram, P. Ohlckers, “Pulsation of InGaAs photodiodes in liquid helium for driving Josephson arrays in ac voltage realization,” IEEE Trans. Appl. Supercond 29, 2019, doi.org/10.1109/TASC.2019.2901573.

[9] O. Kieler, B. Karlsen, P. Ohlckers, E. Bardalen, M. Nadeem Akram, R. Behr, J. Ireland, J. Williams, H. Malmbekk, L. Palafox, and R. Wendisch, “Optical pulse-drive for the pulse-driven AC Josephson voltage standard”, IEEE Trans. Appl. Supercond 29, 2019, doi.org/ 10.1109/TASC.2019.2899851.

[10] N. Flowers-Jacobs, A. E. Fox, P. D. Dresselhaus, R. E. Schwall, and S. P. Benz, “Two-Volt Josephson Arbitrary Waveform Synthesizer Using Wilkinson Dividers”, IEEE Trans. Appl. Supercond. 26(6), 2016 doi.org/10.1109/TASC.2016.2532798.

[11] H. Yamamori and S. Kohjiro, “Fabrication of Voltage Standard Circuits Utilizing a Serial–Parallel Power Divider”, IEEE Trans. Appl. Supercond. 26(8), 2016 doi.org/10.1109/TASC.2016.2622619.

[12] H. Tian, unpublished.