Driving a low critical current Josephson junction array with a mode-locked laser

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01/07/2021 VTT – beyond the obvious

Contents

Acknowledgements

- VTT: T. Fordell, K. Kohopää, E. Mykkänen, P. Immonen, R.N. Jabdaraghi, A. J. Manninen, J. Govenius, and A. Kemppinen
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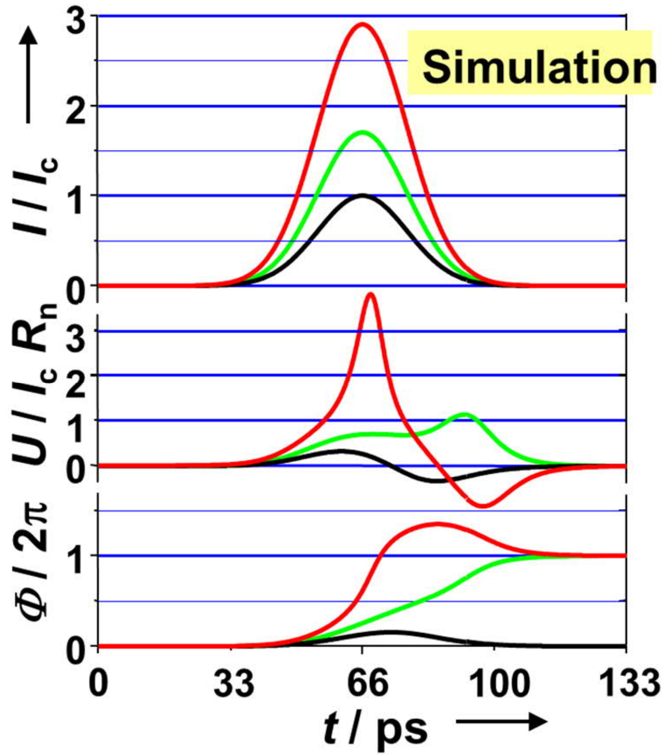
Introduction

Pulse driven Josephson voltage standard

A current pulse is passed through a Josephson junction.

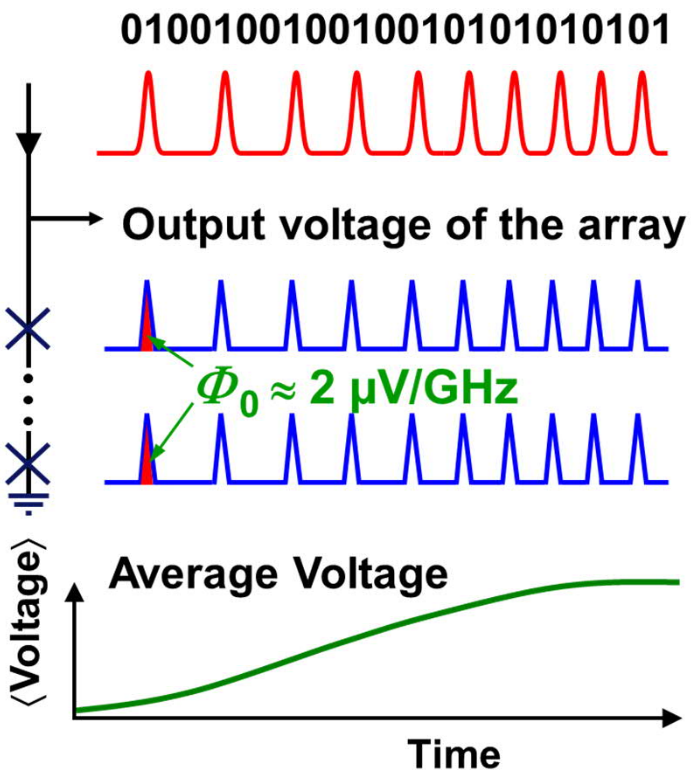
The junction responds by producing a voltage pulse:

$$\int V dt = \pm \frac{N}{K_J}$$



J. M. Williams, T. J. B. 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** 815–818, (2004).

Pulse driven Josephson voltage standard



- Fast Code generator (10 GHz repetition frequency)
- Sequence of input pulses determines output voltage
- Quantised voltage pulses by Josephson junctions
- Increasing of the output voltage by series array
- Positive and negative pulses for bipolar voltages

Slide: Ralf Behr (PTB)

Why optical rather than electrical drive?

Electrical drive	Optical drive
■ Conducted heat 100 mW from room temperature to 4.2 K ■ Dissipation and distortion, bandwidth in some tens of GHz ■ Capacitive coupling between amplifiers and JJA ■ Cross talk and noise ■ Bipolar pulse patterns easy	■ Negligible conduction of heat but dissipation at the photodiode in the cryostat depending on I_c ■ Very high bandwidth, negligible distortion of optical pulses ■ Direct coupling between photodiode and JJA ■ Noise issues to be investigated ■ Bipolar pulse patterns may be challenging

A typical electrically driven assembly with 8 arrays in series and an early stage optically driven assembly

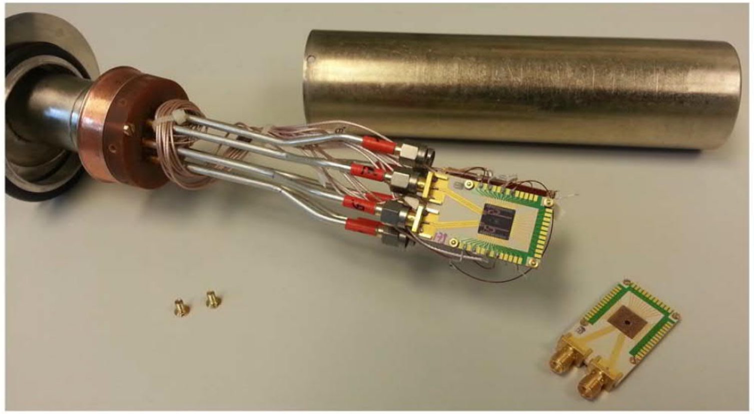


Fig. 5. Photograph of the cold-head of the 8-channel cryoprobe. One chip containing 2 arrays is installed already. A second empty chip carrier [26] and the cryoperm shield are also visible.

O. F. Kieler, R. Behr, R. Wendisch, S. Bauer, L. Palafox, and J. Kohlmann, IEEE Trans. Appl. Supercond. **25**, Art. no. 1400305 (2015).

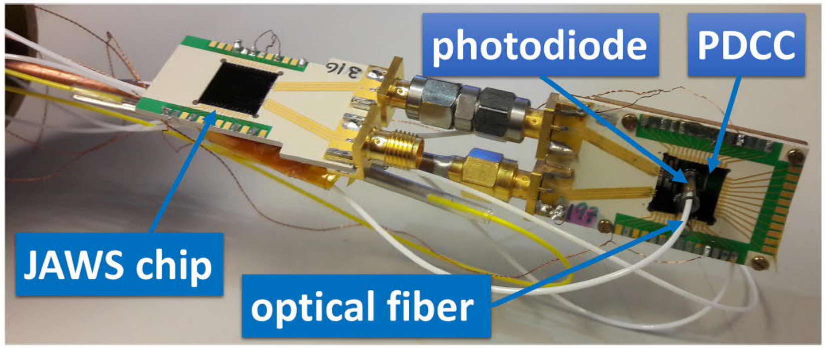


Fig. 2. Photograph showing the JAWS chip (left) and PDCC chip (right) connected. The optical fiber (white) is attached by glass tube guide to the PD mounted by flip-chip to the PDCC chip.

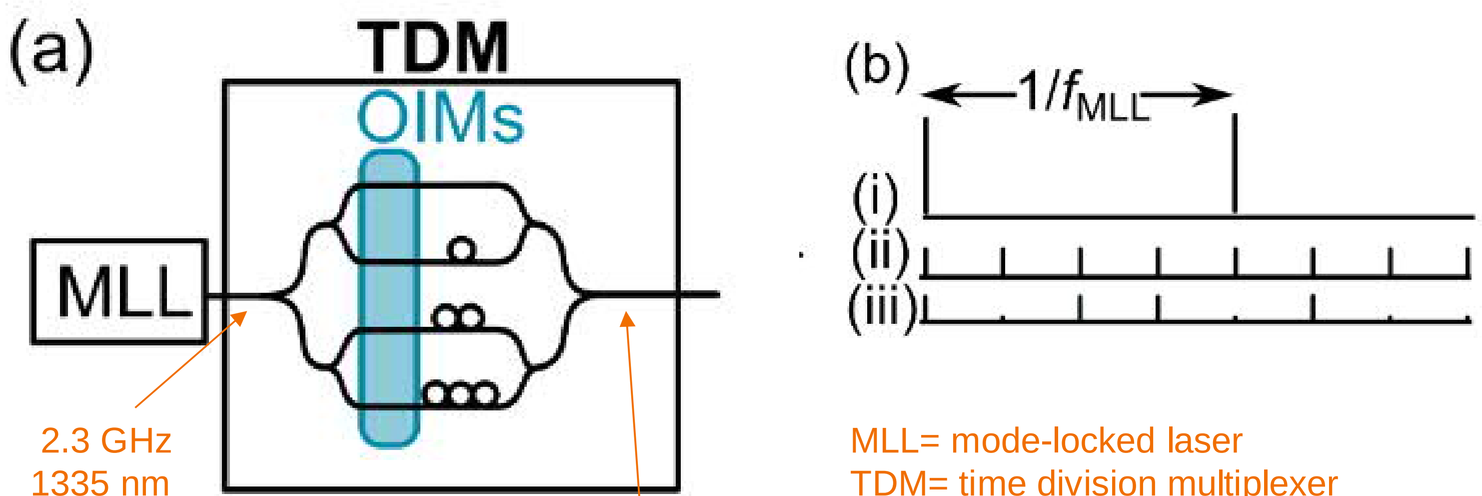
O. Kieler, B. Karlsen, P. A. Ohlckers, E. Bardalen, M. N. Akram, R. Behr, J. Ireland, J. Williams, H. Malmbekk, L. Palafox, and R. Wendisch, IEEE Trans. Appl. Supercond. **29**, 1200205 (2019).

Why a pulsed laser rather than a continuous wave laser and a modulator for pulse shaping?

- Pulses can be very short, easily in the ps range
  - If JJA and photodiode technology allow, pulse frequencies > 20 GHz could be targeted with possibility to increase output voltage without increasing the number of junctions
  - With higher pulse rate higher signal frequencies could be realized
  - With higher frequencies in mind, the challenge remains pulse coding without impairing the original pulse quality as well as photodiode performance
- Mode-locked laser can produce optical pulse trains with minimal jitter (10 attosecond pulse-to-pulse interval spread) and amplitude variation

Experiments

Optical pulse pattern generator



2.3 GHz
1335 nm

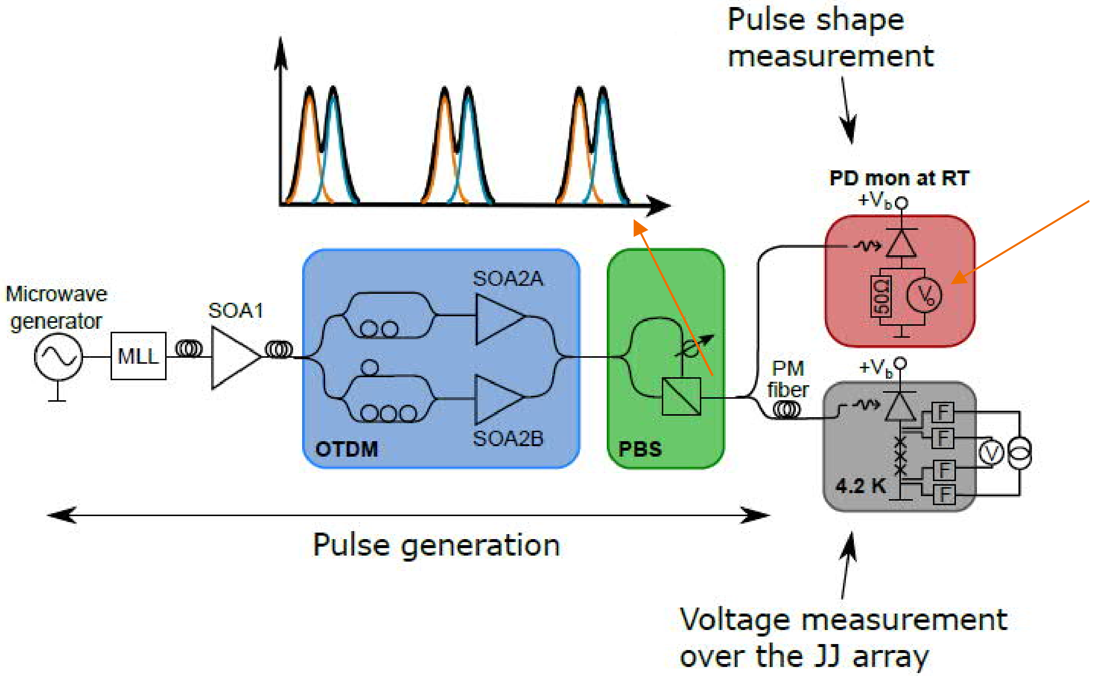
4 x 2.3 GHz
= 9.2 GHz

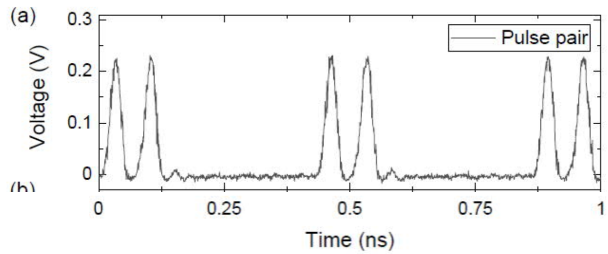
MLL= mode-locked laser
TDM= time division multiplexer
OIM= optical intensity modulator

Modest bandwidth requirement both for the control electronics and optical amplifiers

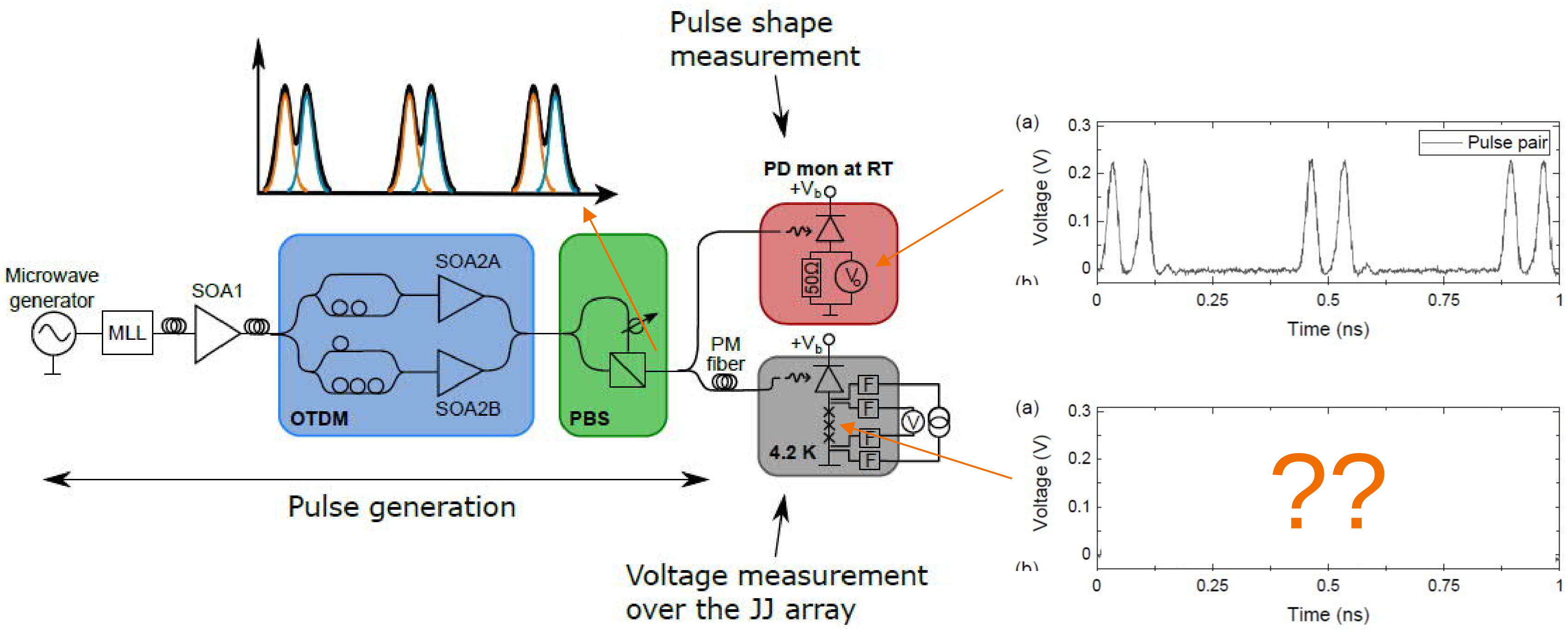
→ Time to settle between state transitions!!

Measurements

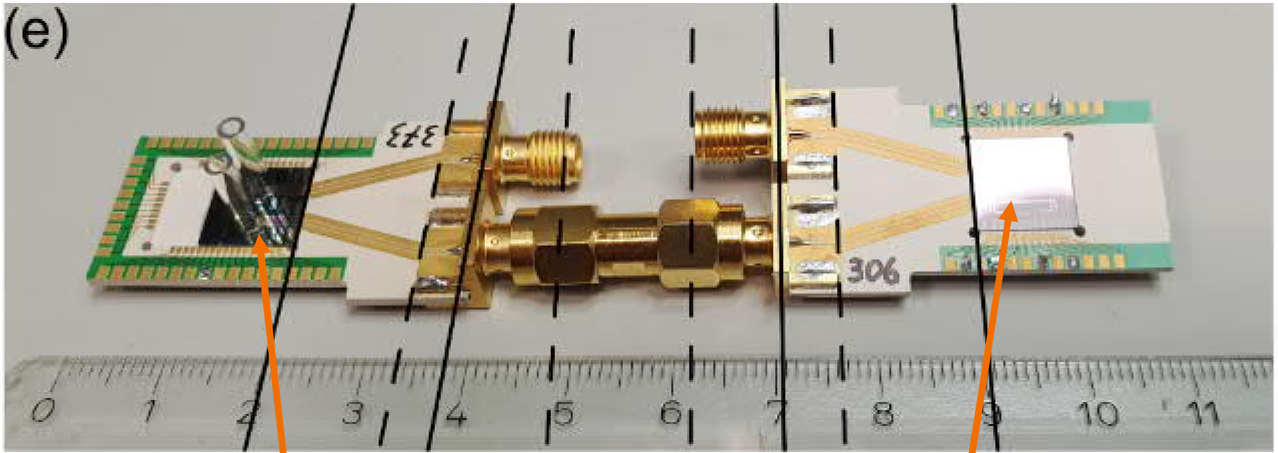




Measurements



Photodiode-JJA assembly



Photodiode (Albis Optoelectronics AG, InGaAs/InP p-i-n, 28 Gbits/s)

JJA (PTB, 1000 Nb-Nb$_x$Si$_{1-x}$-Nb JJs, Ic=0.36 mA, fc=5.4 GHz)

Measurement results (voltage mapped against current pulse integral and dc current)

Measurements

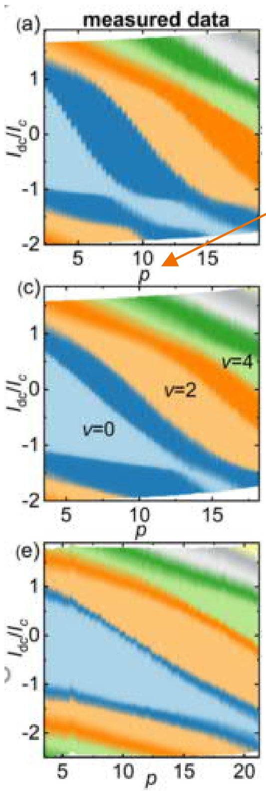
Normalized pulse current integral p

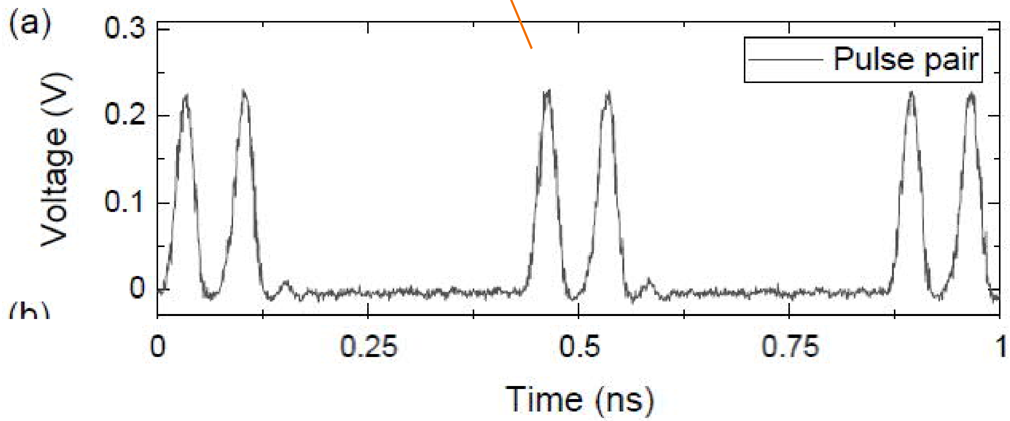
$$p = \frac{2\pi f_c}{I_c} \int_0^{1/f_{MLL}} I_p \, dt, \text{ where } I_p = I - I_{dc}$$

Δt of 30 ps ((a) and (b))

Δt of 95 ps ((c) and (d))

Δt of 220 ps ((e) and (f))





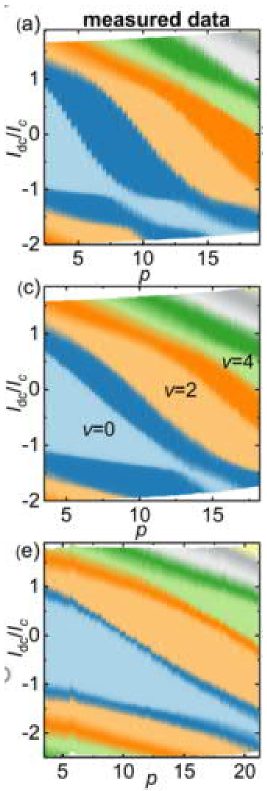
"Δt of 95 ps" corresponds to a measurement where pulse pairs with pulse interval of 95 ps was used to drive the array. The repetition rate of pulse pairs was 430 ps (=1/2.3 GHz).

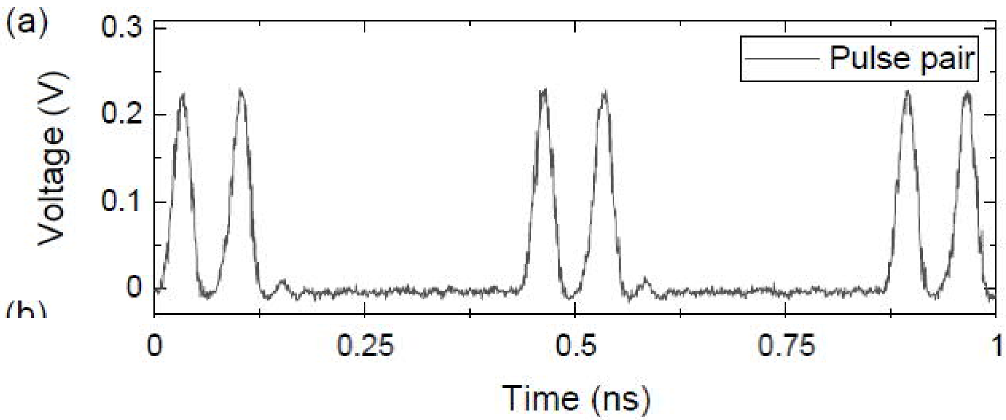
Measurements

Δt of 30 ps ((a) and (b))

Δt of 95 ps ((c) and (d))

Δt of 220 ps ((e) and (f))

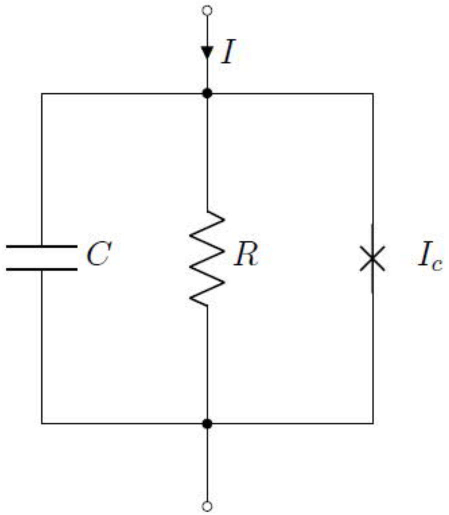




Are the data in agreement with simulations?
Is the experimental system in good control?

Simulations of voltage maps

Resistively and capacitively shunted JJ model for a single junction



$$I = I_c \sin\phi + \frac{\hbar}{2eR}\frac{d\phi}{dt} + \frac{\hbar C}{2e}\frac{d^2\phi}{dt^2}.$$

Figure 2.7: Equivalent circuit model for a Josephson junction containing a capacitor, a resistor and a Josephson junction in parallel.

Resistively and capacitively shunted JJ model for a single junction

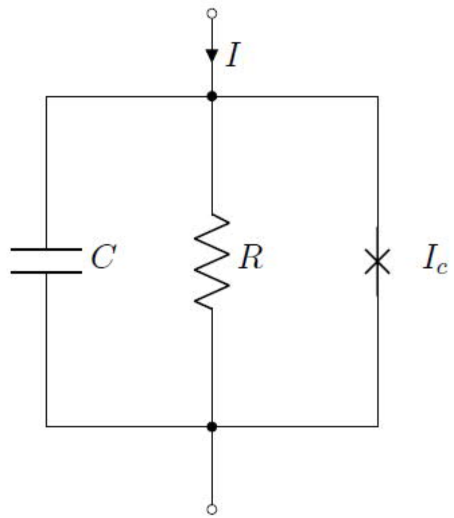


Figure 2.7: Equivalent circuit model for a Josephson junction containing a capacitor, a resistor and a Josephson junction in parallel.

$$I = I_c \sin\phi + \frac{\hbar}{2eR}\frac{d\phi}{dt} + \cancel{\frac{\hbar C}{2e}\frac{d^2\phi}{dt^2}}.$$

C small

Simple solution using discrete time steps:

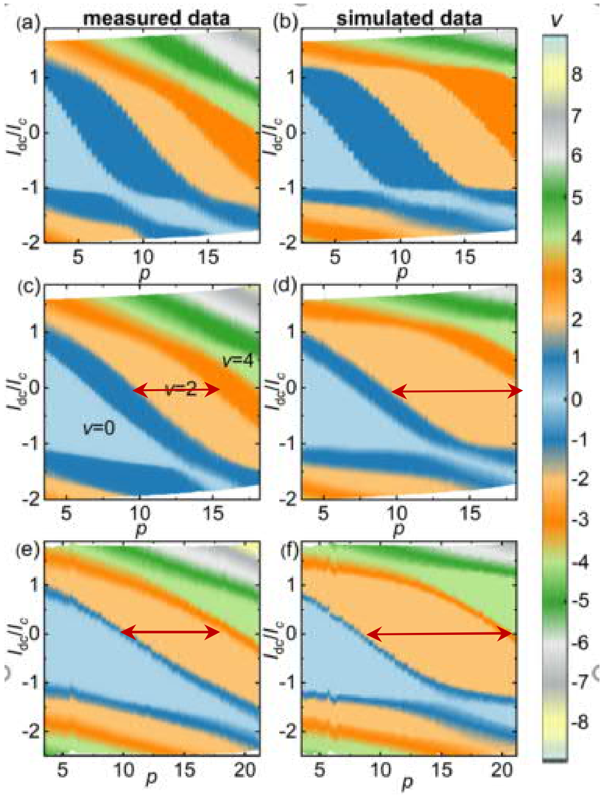
$$\phi_j = \phi_{j-1} + d\phi_{j-1}dt$$

Voltage vs pulse amplitude and dc current

Δt of 30 ps ((a) and (b))

Δt of 95 ps ((c) and (d))

Δt of 220 ps ((e) and (f))



Here, the simulated data were obtained from single-JJ RSJ calculations

Simulations predict much wider even numbered steps than observed in the measurements

Josephson junction array (PTB, Ic=0.36 mA)

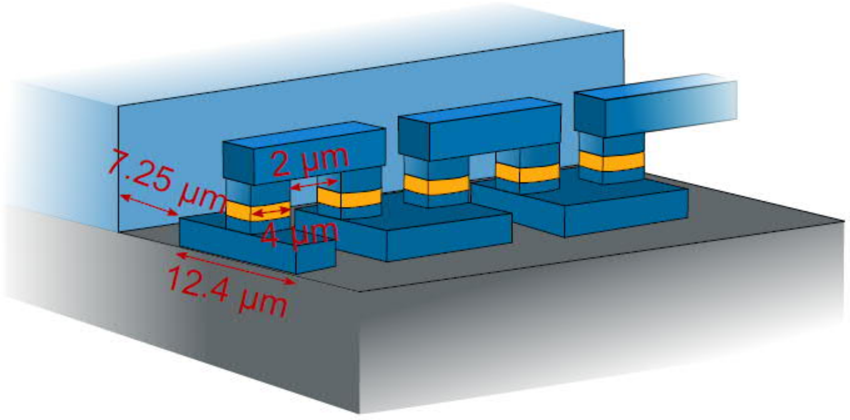


Figure 3.5: Sketch of the geometry of the JJA. The pillars represent the Josephson junctions and the orange parts are normal metal. The central line width and the gap width are presented. Here, the gap width corresponds to that of the beginning of the Josephson junction array, and the gap width decreased through the array. In addition, the distance between adjacent Josephson junctions and the length of the junctions is shown. Figure based on [6].

JJA model with junctions embedded in a superconducting transmission line (tapered)

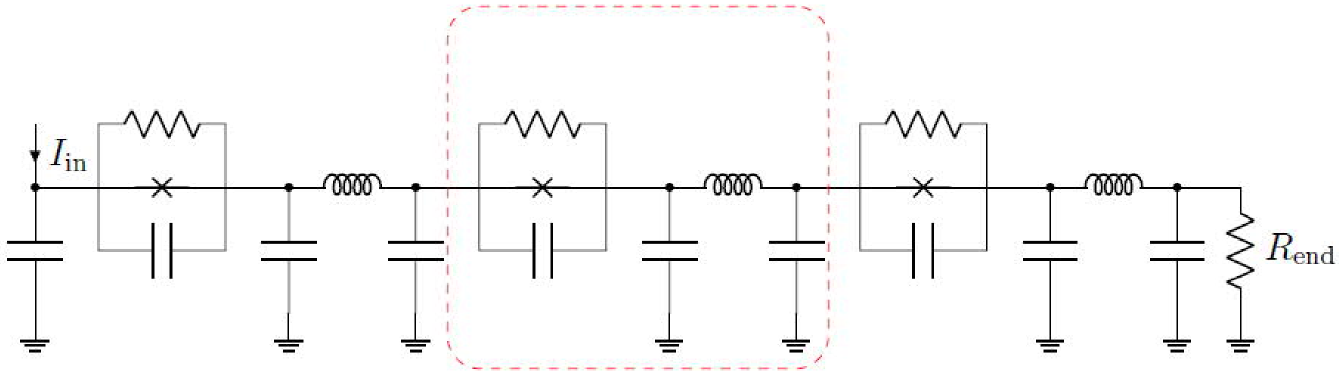


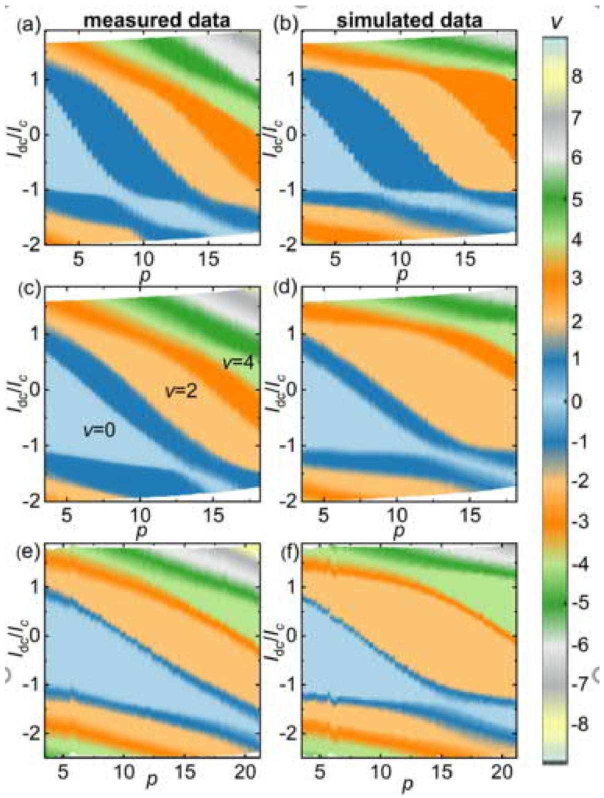
Figure 4.2: Josephson junction array (JJA) circuit model with many Josephson junctions. One JJA unit is circled with red dashed line. For simplicity, only three units in series are presented. The JJA is driven with an ideal current source I_{in}, and the array is terminated with a resistor R_{end}.

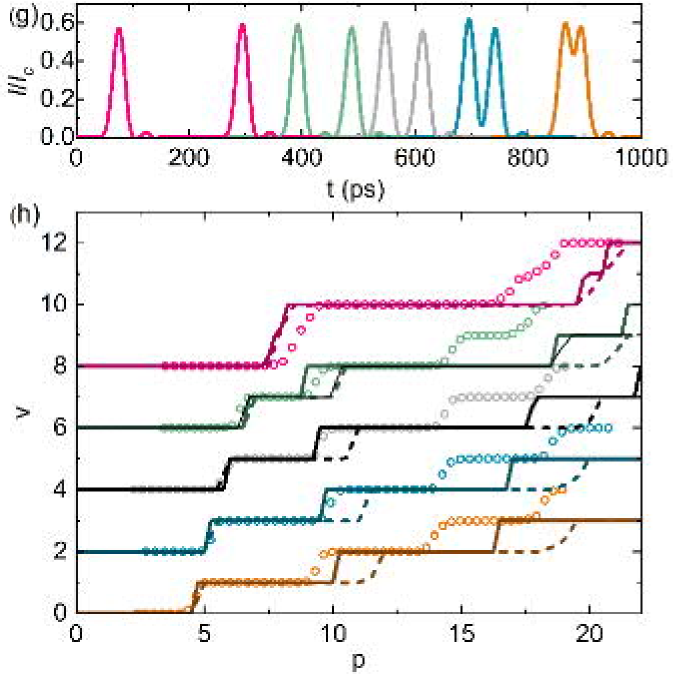
Voltage vs pulse amplitude and dc current

Δt of 30 ps ((a) and (b))

Δt of 95 ps ((c) and (d))

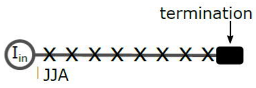
Δt of 220 ps ((e) and (f))





circles = the experimental values,
solid lines = the simulated results using a single-JJ model
dashed lines = the simulated values using a transmission line model for the JJA (1000 JJ) and an unterminated photodiode in 10 mm long 50 Ω transmission line.

What do the simulations tell in time domain?



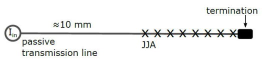


Figure 4.5: Illustration of the simulation model with the 10 mm passive transmission line and the Josephson junction array. In addition, the model contains the external current source I_{in} and at the end, the JJA is terminated with a resistor.

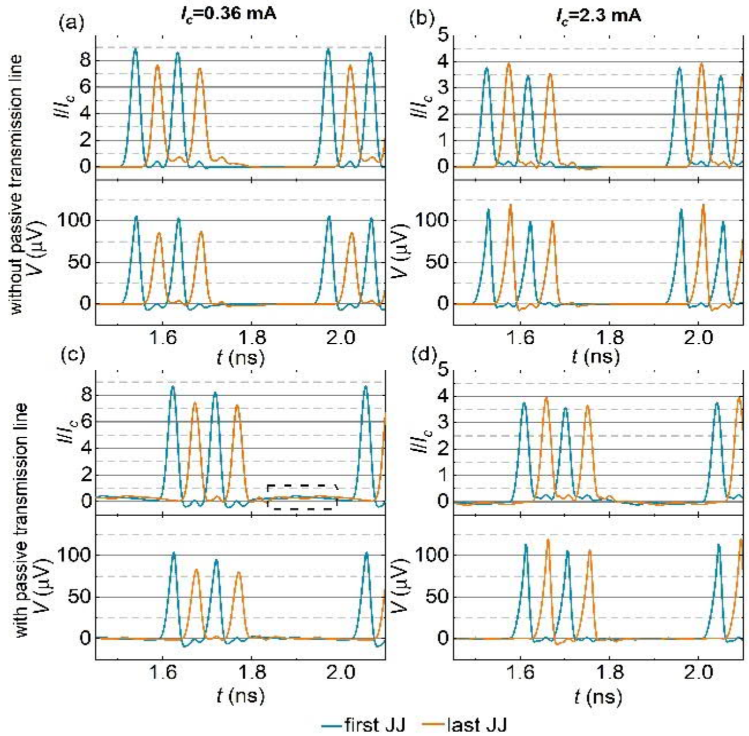


Fig. 3. Simulated current pulse waveforms through and voltage pulse waveforms across the first and last JJ in a JJA for arrays A and B with two pulses separated by 95 ps. Panels (a)-(b) show the simulated current and voltage for the case without any transmission line between PD and JJA for arrays A and B, respectively. Panels (c)-(d) show the corresponding simulations when there is a 10 mm transmission line between PD and JJA. The simulations shown here were performed in the middle of plateau $v = 2$. Note the amplitude of current fluctuation $I_c/2$ in the background (dashed box).

Fluctuating current background due to pulse reflections in the photodiode-JJA assembly is expected to be the main origin of discrepancy between experiments and simulations.

Mounting of the PD close to the JJA is expected to improve performance

Conclusions and outlook

Conclusions and outlook

- A concept of an optical pulse pattern generator based on a mode-locked laser and a time division multiplexer has been developed
  - MLL may be designed and built to produce ps pulse trains with extremely low jitter and amplitude spread
  - TDM may be designed and built to multiply the pulse rate and carry out pulse picking (pattern formation) without markedly deteriorating the MLL pulse quality
- In the proof-of-concept experiments of this work, comparison between measurements and simulations showed that in the future, the PD should be mounted close to a JJA, and the PD should possibly be matched to the transmission line with a resistive shunt
- With development of both JJA and photodiodes towards operating at higher pulse rates, both utility signal amplitude and frequency range could be expanded from what is state-of-the-art using all-electronic pulse drive techniques.
- The cost of the technique could be competitive

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