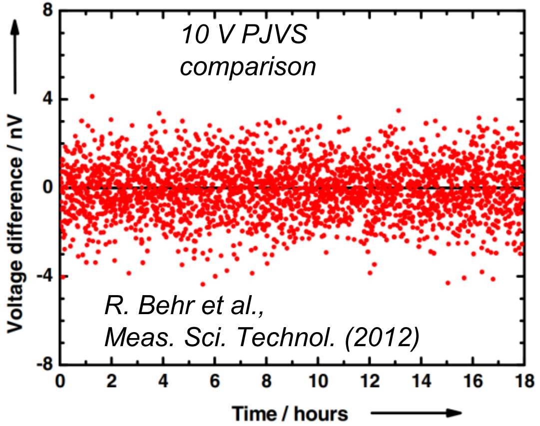
Erweiterung des Josephson Arbiträrwellengenerators: Eine quantengenaue GHz-Quelle

Michael Haas, Abdulrahman Widaa, Oliver Kieler, Marco Kraus,
Ralf Behr, Johannes Kohlmann, and Mark Bieler

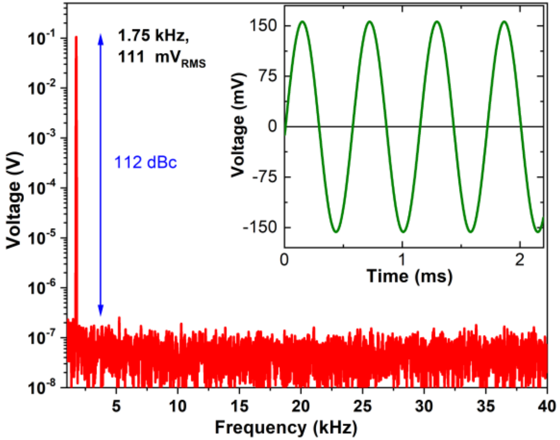
Motivation: existing (Josephson) systems

Quantum standards established
for dc and low frequency voltages
→ e.g. 10 V dc with PJVS standard



Newest generation of ac voltage standards:
Josephson **A**rbitrary
Waveform **S**ynthesizer (**JAWS**)
→ Established for ≥ 100 kHz

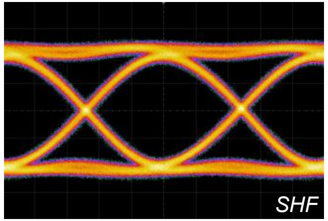
Most important:
- spectrally pure
- low noise
- programmable waveforms

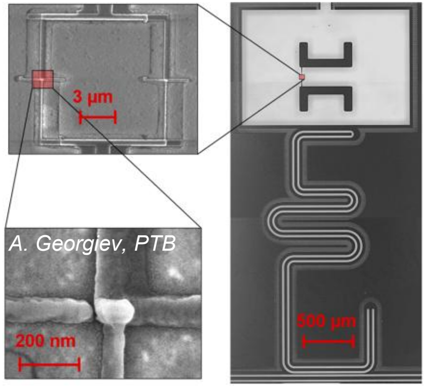


Motivation: higher frequencies

- Recent demands for GHz extension

- Possible applications include:
  - Microwave metrology, potentially replacing calorimetric standards
  - Telecommunication
  - Radar
  - Qubits



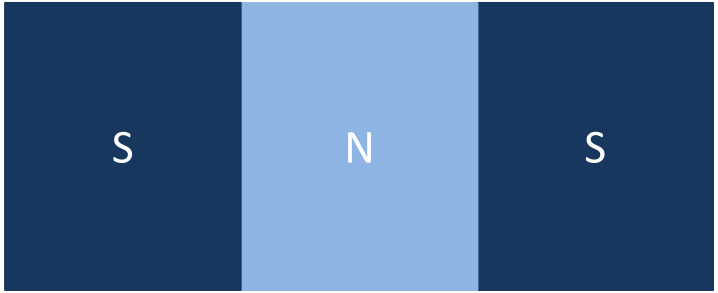


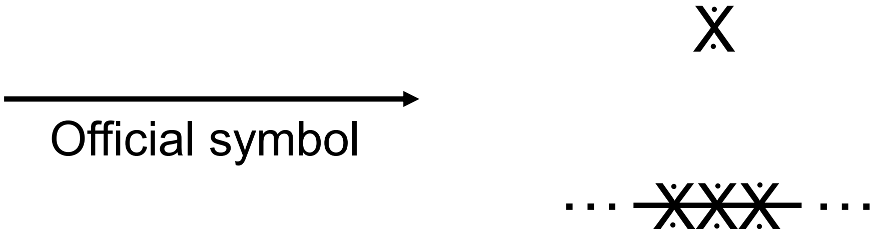
→ Extension of JAWS output frequency to GHz

Content

- JAWS introduction
- Problems at GHz
- Approach 1: Pulse shaping
- Approach 2: Filters
- Conclusions

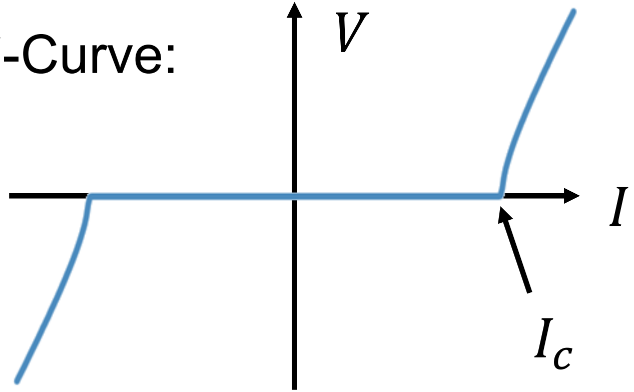
Josephson junction (JJ)





Nb $Nb_{1-x}Si_x$ Nb

IV-Curve:



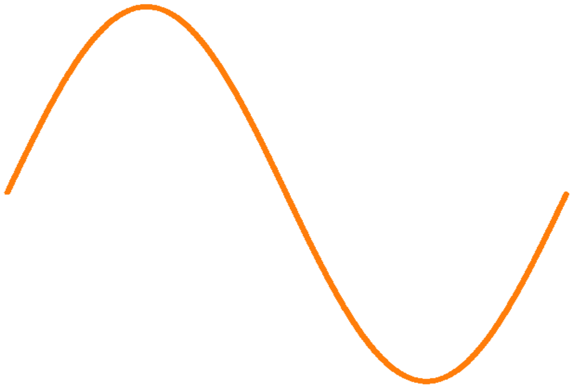
S: Superconductor

N: Normal conductor

Shapiro steps

$$V_m = N \cdot m \cdot \Phi_0 \cdot f_{app}$$

$+$



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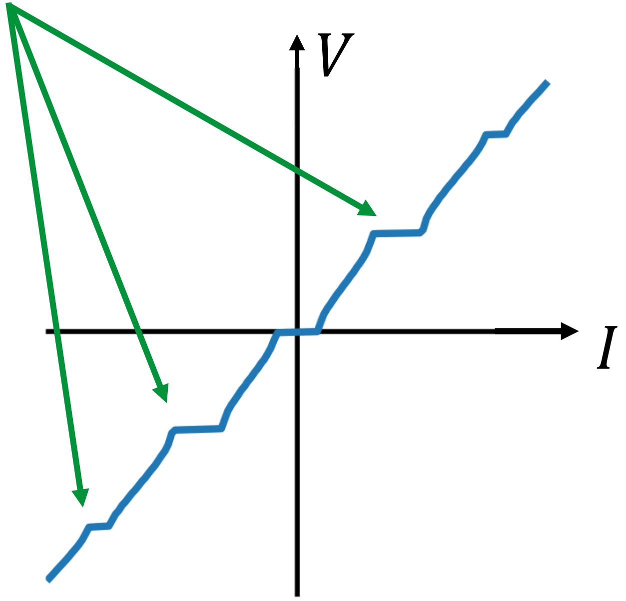


N junctions

Quantized voltage pulses $\int V(t)dt = \Phi_0 = \frac{h}{2e}$

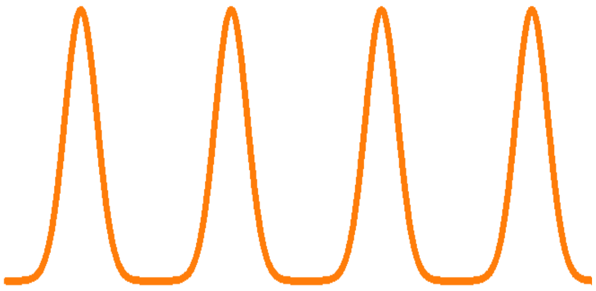
$\rightarrow$ quantized dc response

Pulsed Shapiro steps

$$V_m = N \cdot m \cdot \Phi_0 \cdot f_{app}$$

N junctions

+



S. Benz, C. Hamilton, Appl. Phys. Lett. 68 (1996)

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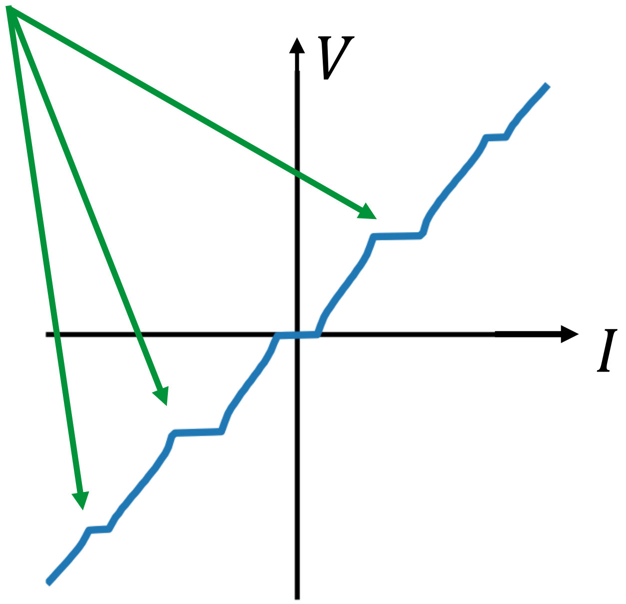
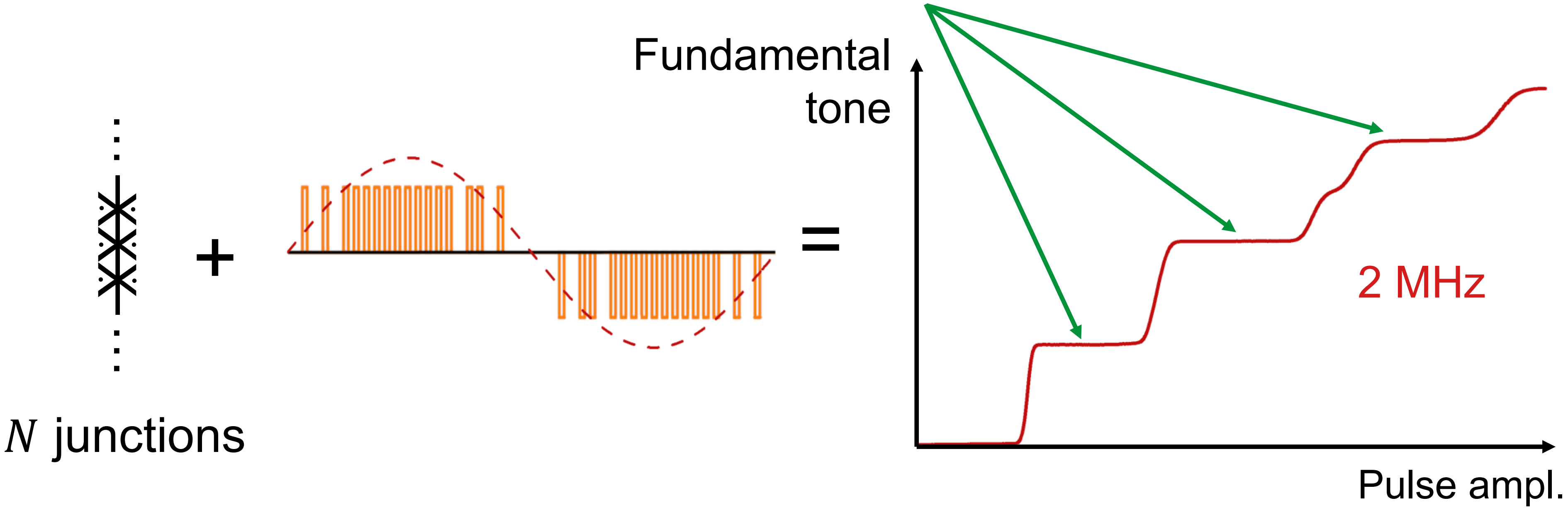


Quantized dc voltage(s)

Basis for JAWS

$$V_m(t) = N \cdot m \cdot \Phi_0 \cdot f_{app}(t)$$



S. Benz, C. Hamilton, Appl. Phys. Lett. 68 (1996)

Quantized **ac** voltage(s)

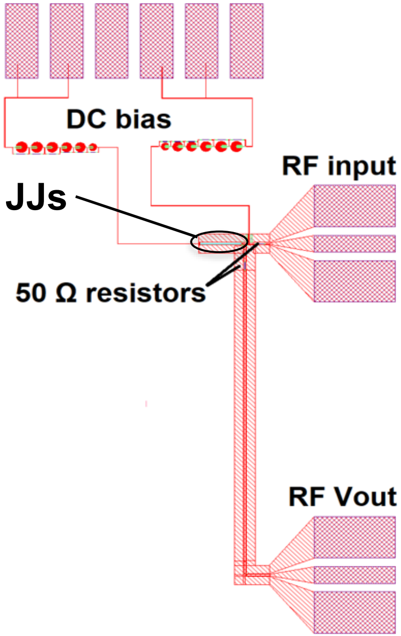
Setup and an example: lumped array

Amplifier

AWG

HF spectrum analyzer

Dipstick + chip (e.g. 36 JJs lumped array) in LHe



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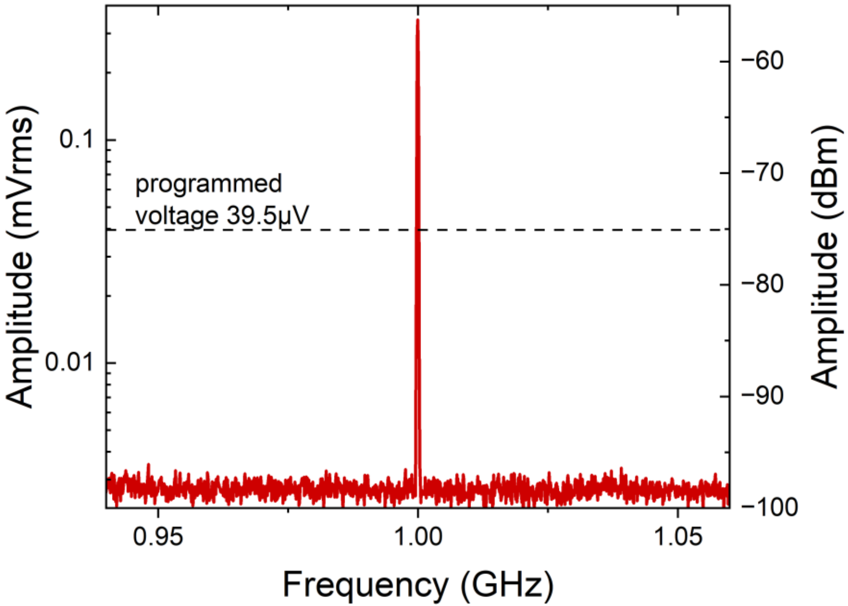
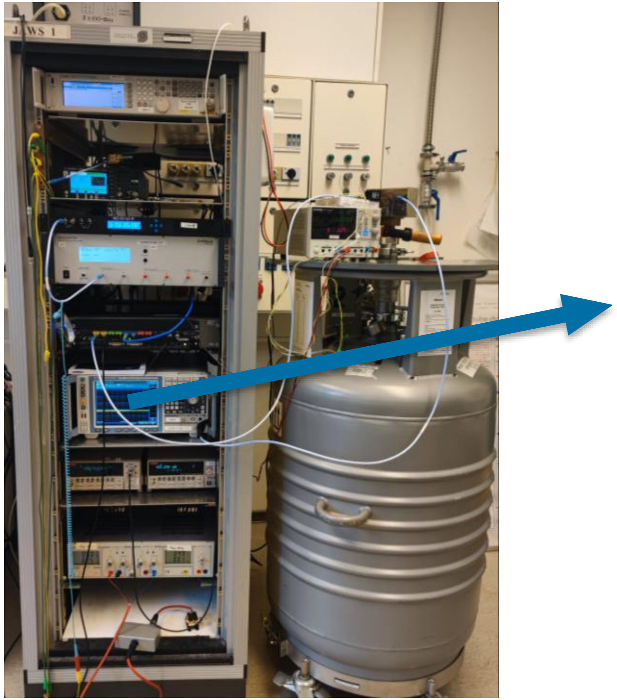
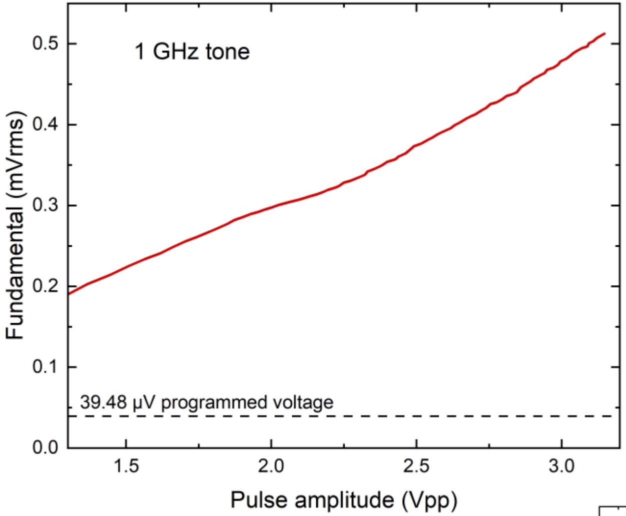
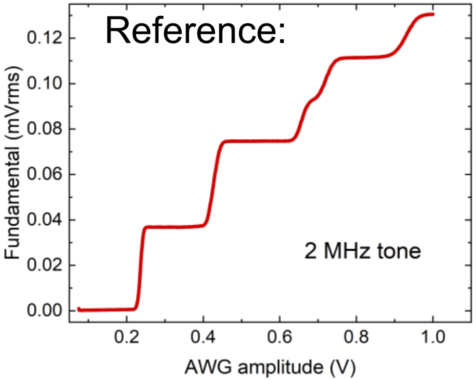
Setup and an example: lumped array



Setup and an example: lumped array

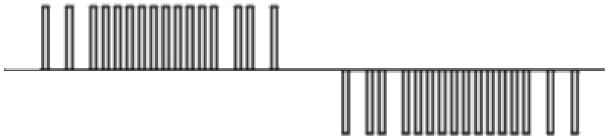






Feedthrough (FT) and zero compensation

$V_{FT}(t) \sim$



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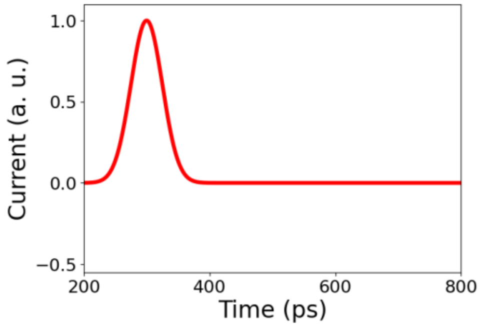
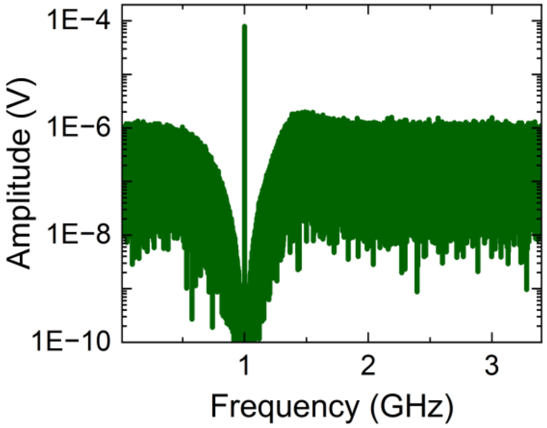


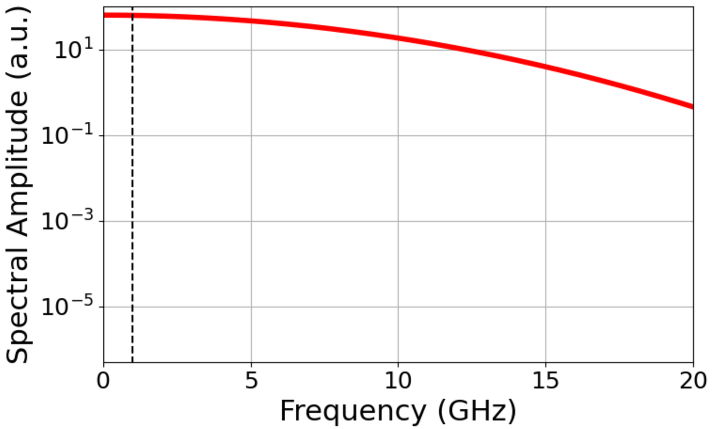
FFT

FFT

$V_{FT}(f) \sim$



x



C. Donnelly et al., IEEE TAS (2020)

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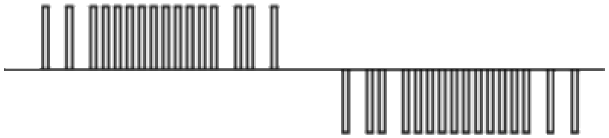

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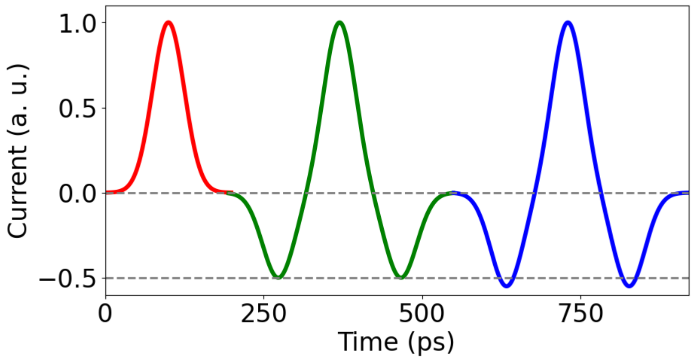

FFT

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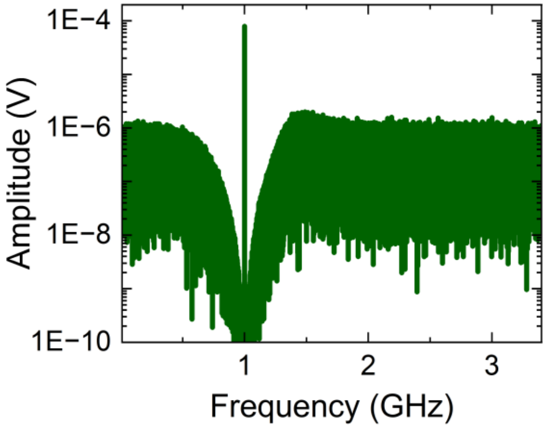

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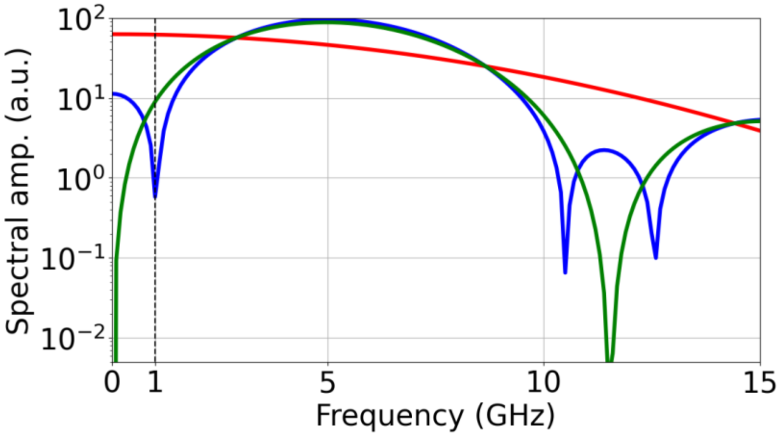
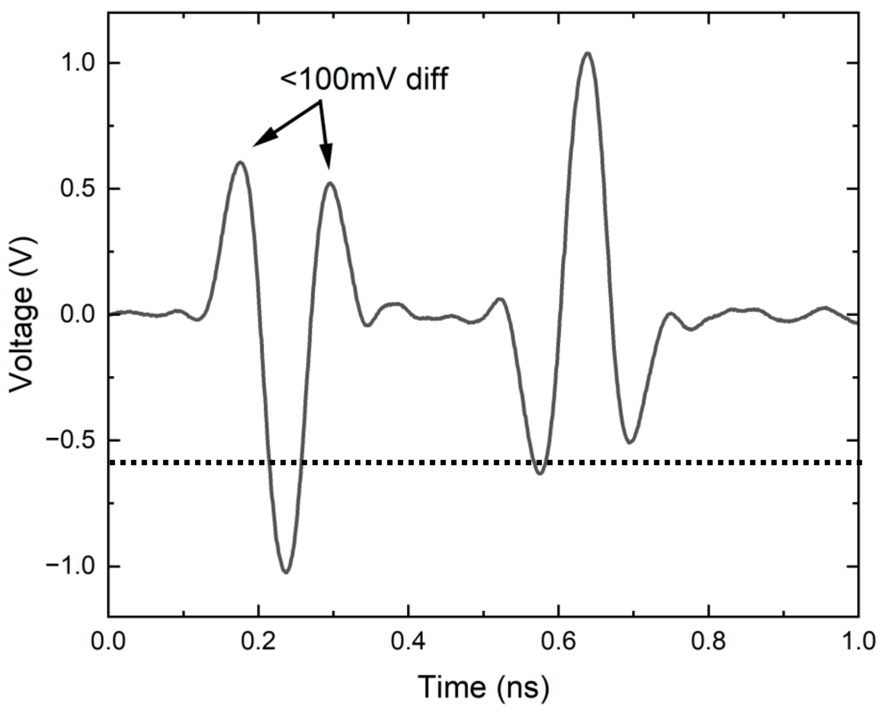
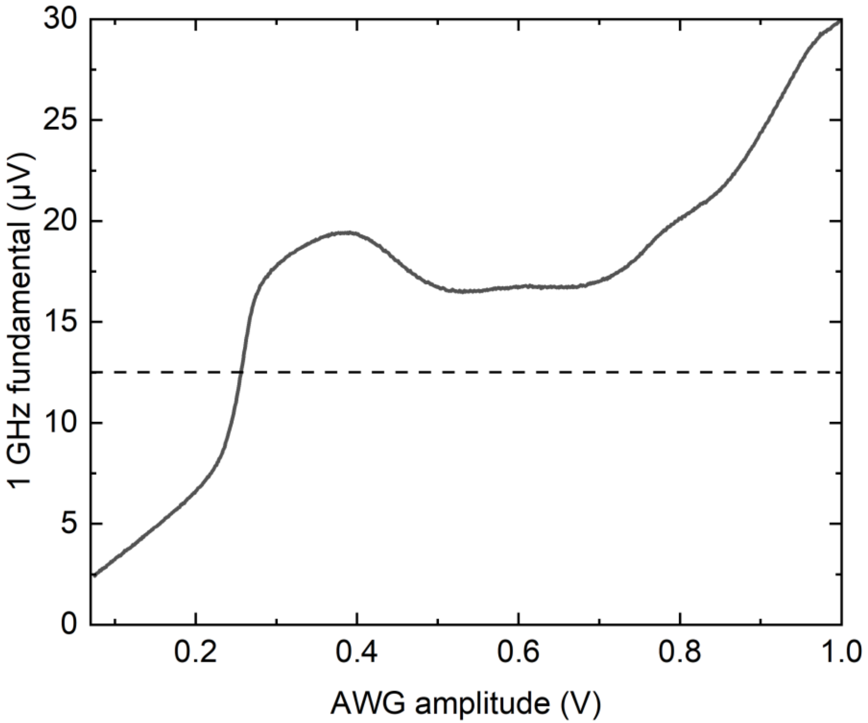


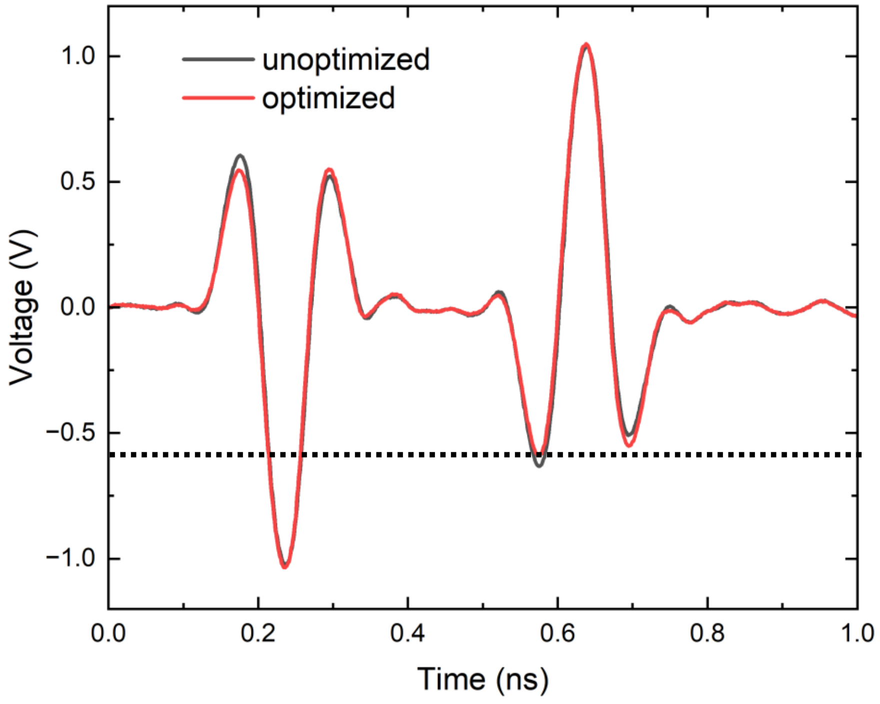
C. Donnelly et al., IEEE TAS (2020)

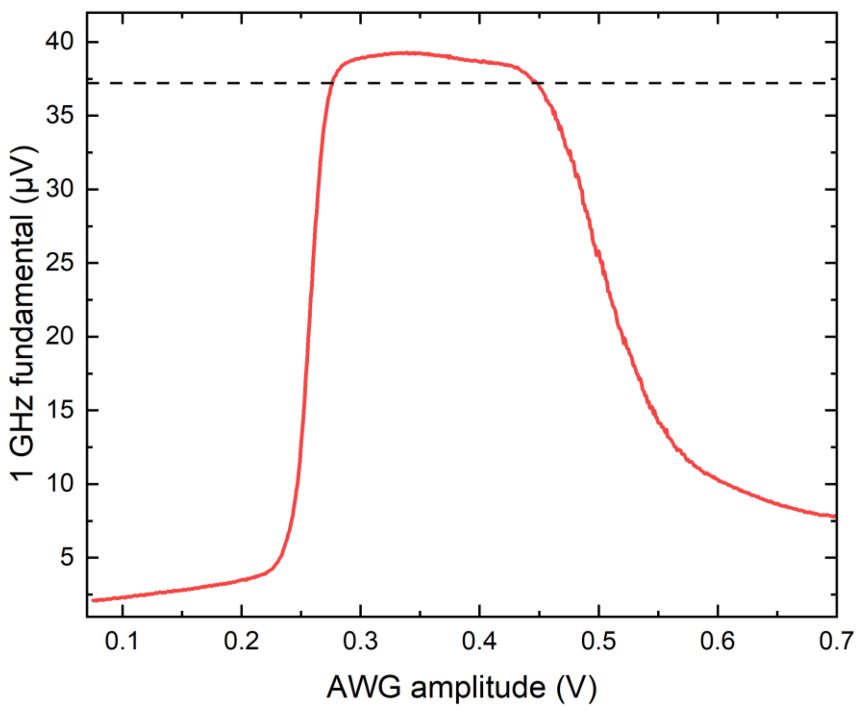
Basic pulse optimization



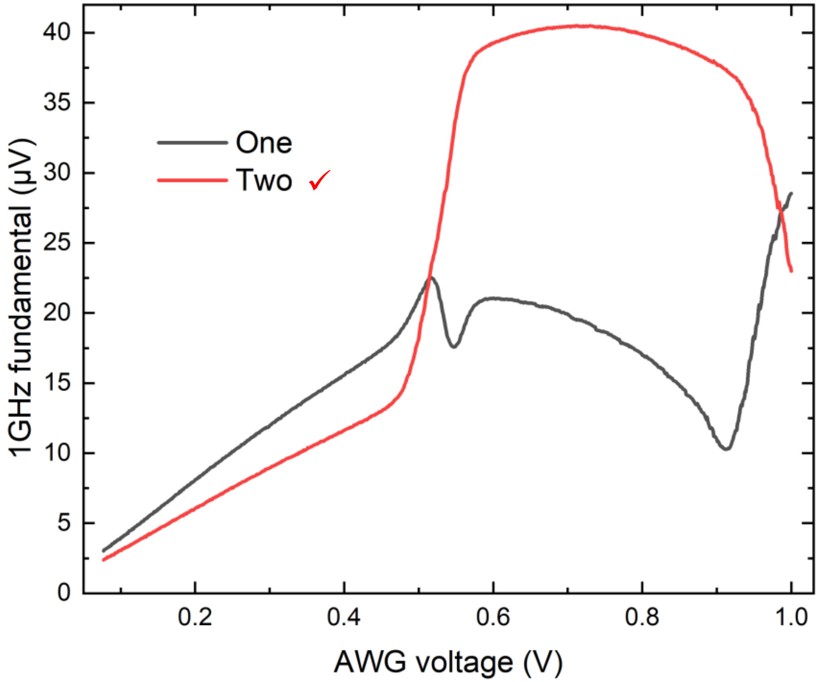


Basic pulse optimization





Optimizing pulses "in the dark"

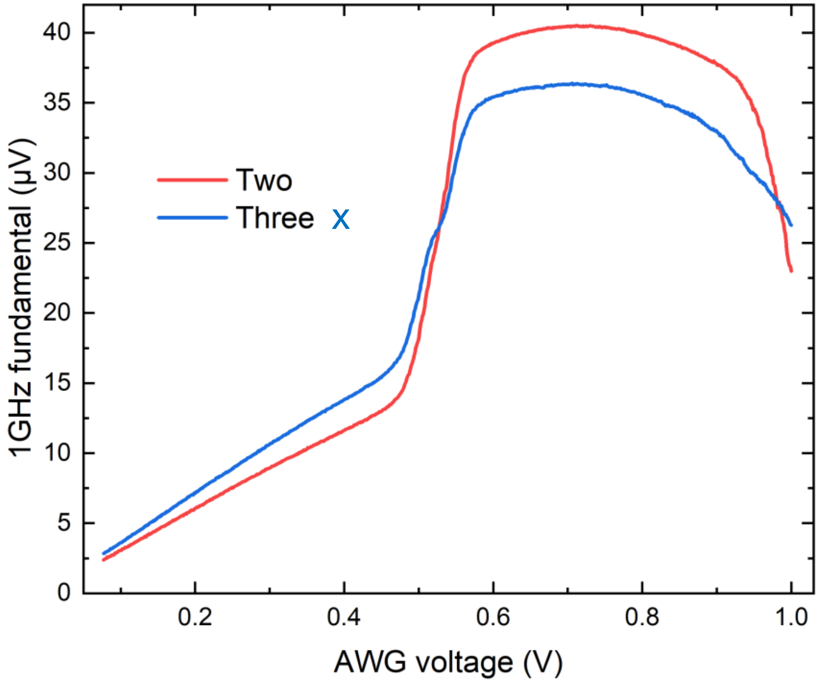


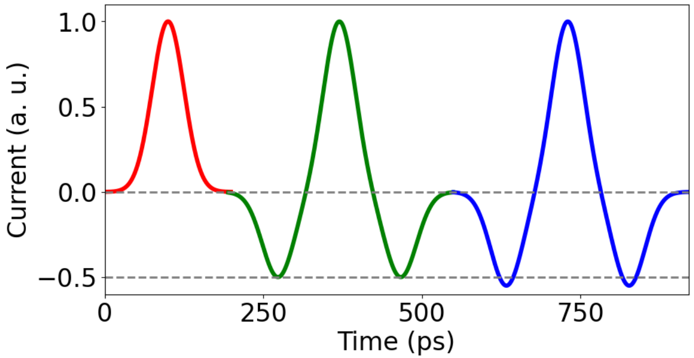
- Change one of the sidelobes
- Check feedthrough (0th step slope)

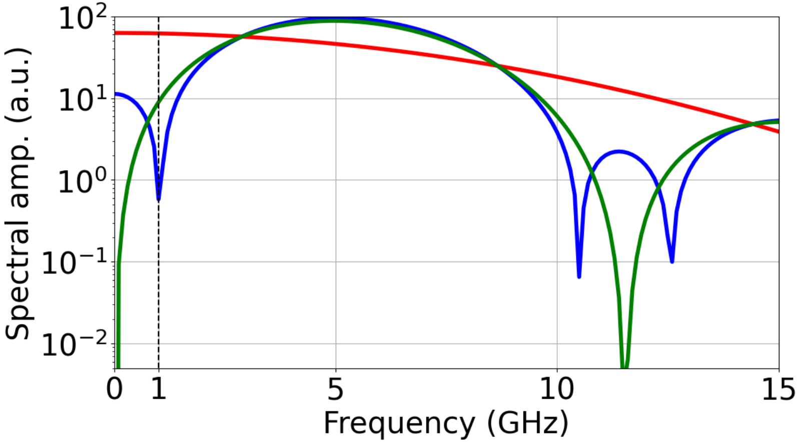
- Reduced (red curve)
  → keep good change

- Increased (blue curve)
  → discard bad change

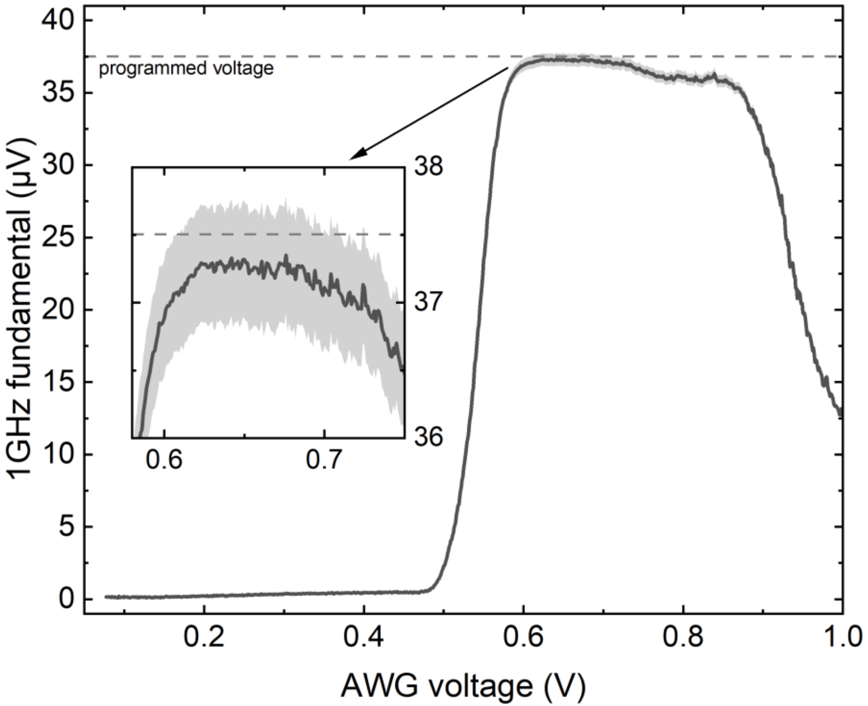
Optimizing pulses "in the dark"





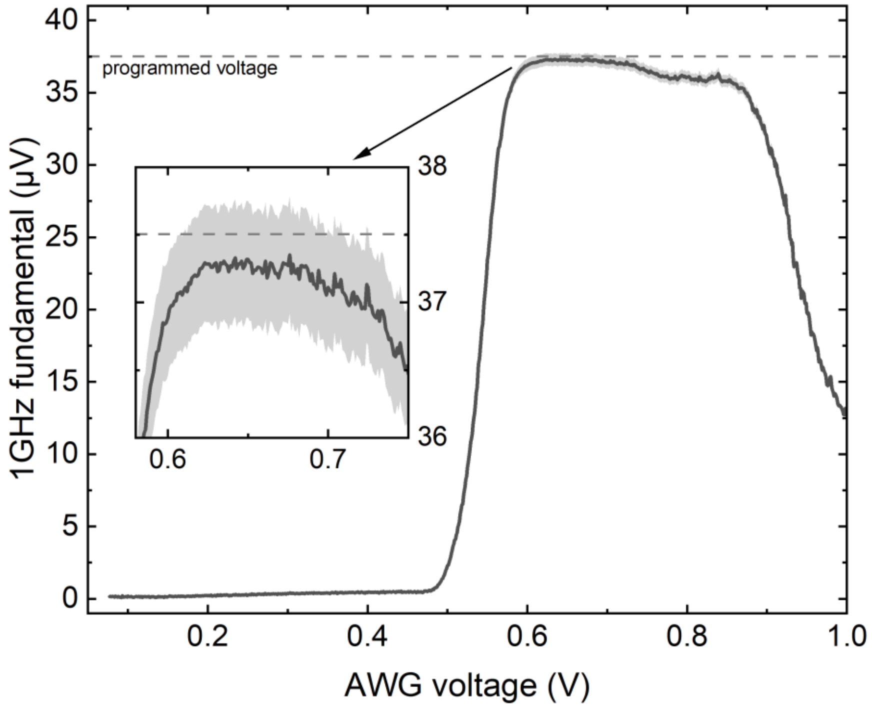


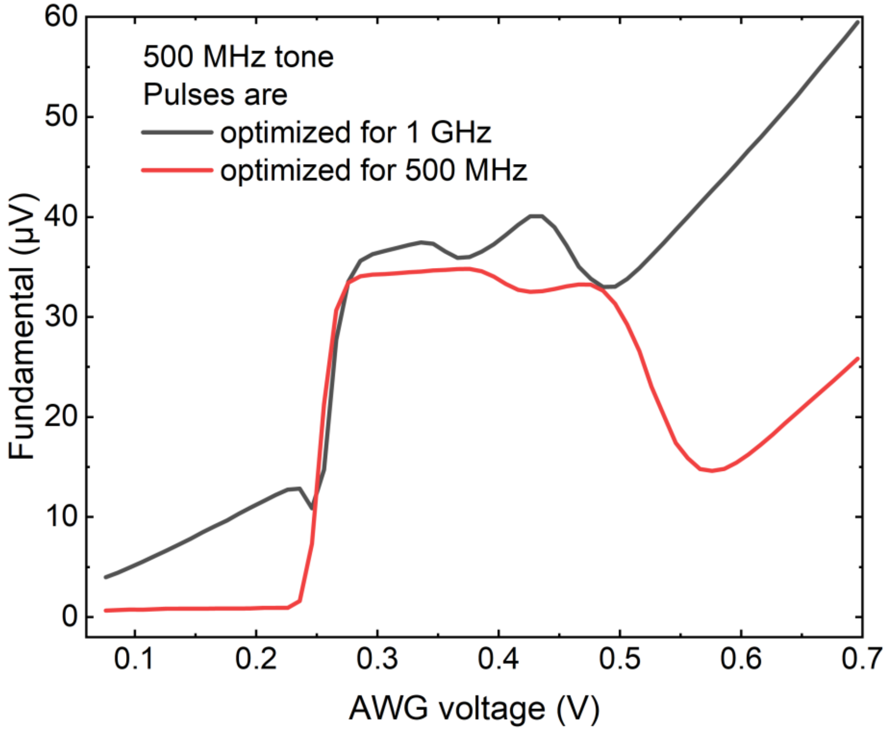
The optimized result



- 36 JJs at 1 GHz, no filters
- Feedthrough ~35dB below total measured signal
- Deviations < 1%
  → also explainable by $\pm$0.1dB of cable attenuation

Frequency dependence of optimization





Great result, but: still only 36 JJs, limited voltage

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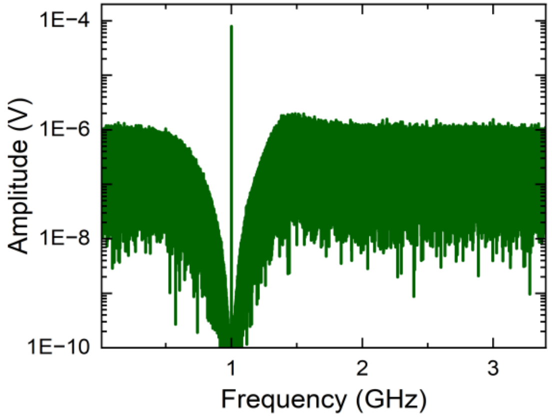
Second approach: filters

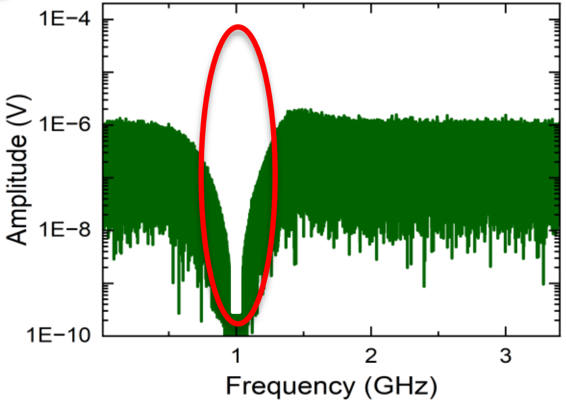
input signal

band-stop filter

filtered input signal

long JJ array (>1000 JJ)



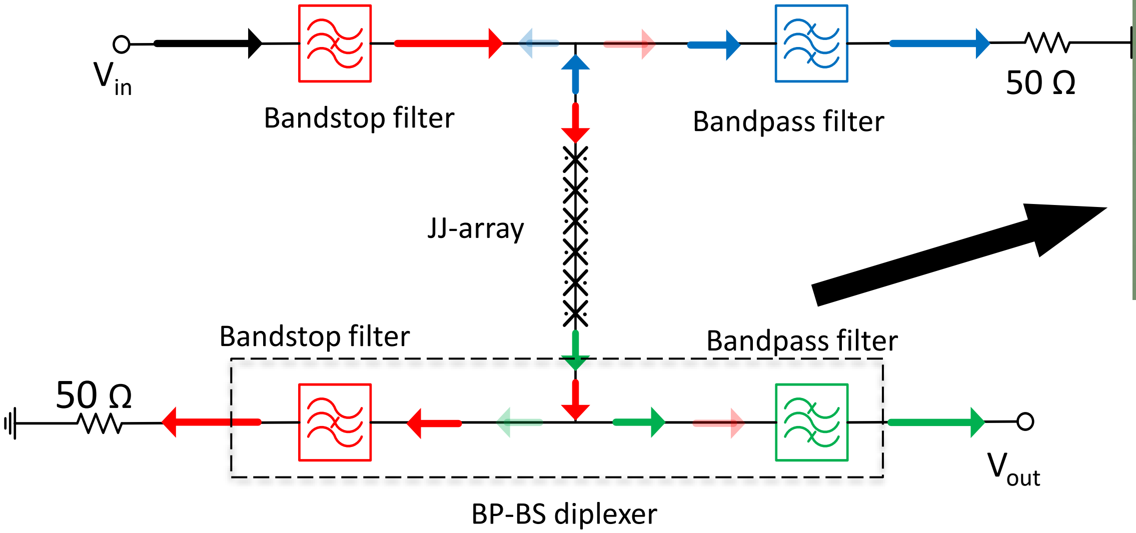


In detail: more complicated

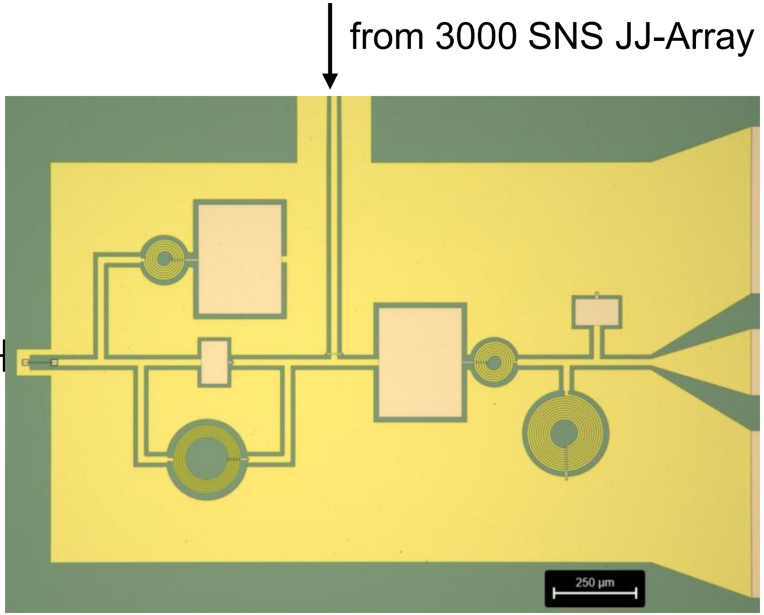
A. Widaa et al., EuMW (2025)

Diplexer layout

- Input contains target frequency
- Complex filter layout to reduce feedthrough
- Allows for longer JJ arrays → higher output



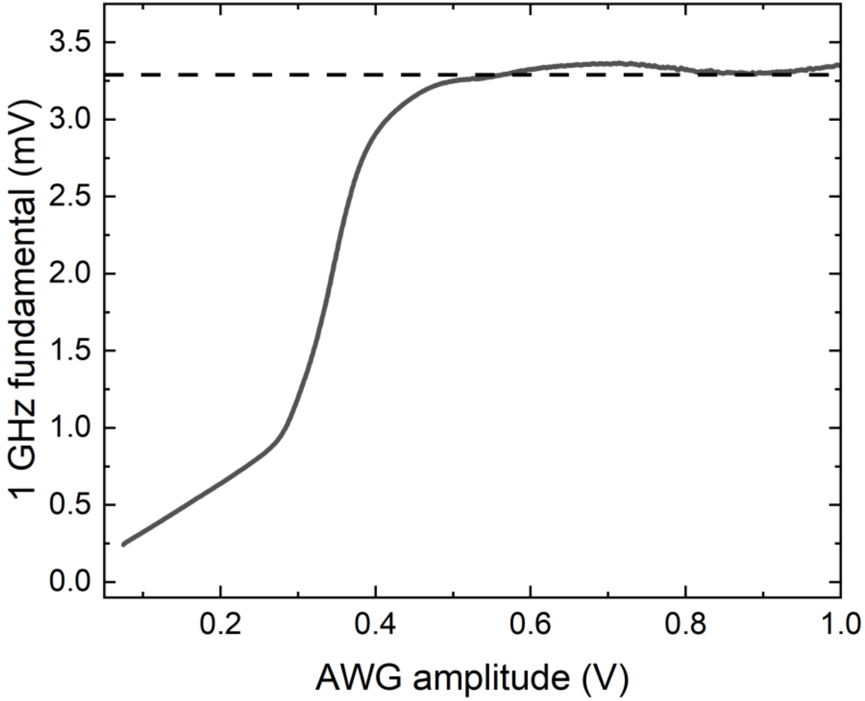
from 3000 SNS JJ-Array

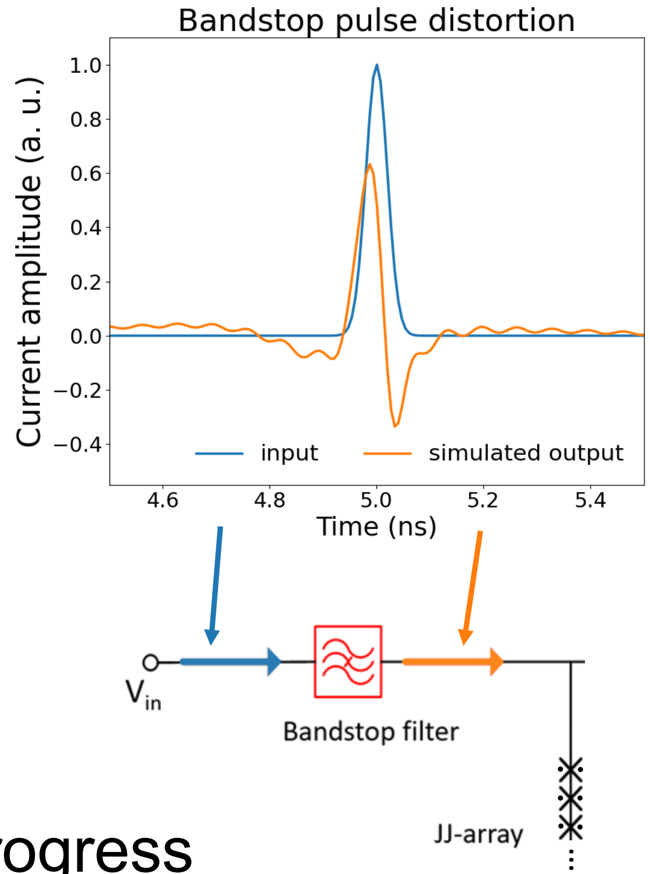


1 GHz second order diplexer example

A. Widaa et al., EuMW (2025)
C. Donnelly, dissertation (2019)

Diplexer chip results





Optimization in progress

Summary

✓ New GHz JAWS setup established

✓ Successfully completed thorough feedthrough investigations

→ extremely sensitive to time domain pulse shape

✓ Found an optimal drive different from state-of-the-art drive

✓ µV @ GHz demonstrated (~ -75 dBm), error ~35 dB below total signal

➢ Diplexer & mV (~ -40 dBm) @ GHz investigations ongoing

➔ What does the community need?

Questions?

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Michael Haas
Working groups 2.41 & 2.42
Phone: +49 531 592-2456
E-Mail: michael.haas@ptb.de

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METROLOGY PARTNERSHIP

EURAMET

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