DC-SQUID readout with high dynamic range and intrinsic frequency-division multiplexing capability

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dc-SQUID basics

dc-SQUID = magnetic flux to voltage/current converter

- periodic $V/I - \Phi$ characteristic
- linear flux range: $\Phi_{\text{lin}} \sim \Phi_0 / \pi$  \(\rightarrow\) flux-locked loop
- intrinsically ‘infinitely’ large dynamic range
- very high signal bandwidth: $R/L \sim 100\,\text{GHz}$
flux-locked loop (FLL)

overall flux in SQUID is kept constant by applying flux feedback compensating variations caused by input signal
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![Diagram of FLL circuit]

disadvantages / challenges:

- cable delay $t_d$
  - FLL bandwidth < intrinsic SQUID bandwidth
  - slew rate (1-10 $\Phi_0/\mu s$)

- integrator
  - automatic reset for preventing FLL running into saturation slew rate limitation!

AD-converter
analog-to-digital converter (ADC)

FLL-output signal has to be compatible with input range of digitizer

signals smaller than the Least Significant Bit (LSB) can not be resolved
analog-to-digital converter (ADC)

dynamic range: ratio between largest and smallest value a quantity takes

\[ DNR = 20 \log \left( \frac{2\Phi_{\text{max}}}{\Phi_{\text{noise}} \sqrt{\Delta f}} \right) \]

ADC resolution: number of discrete values over the full range of analog values

\[ \Delta V_{\text{ADC}} = \frac{V_{\text{max}} - V_{\text{min}}}{2^M} \]

\( M \): ADC resolution (#bits)

example: SQUID with \( \sqrt{S_\Phi} \sim 0.1 \mu \Phi_0/\sqrt{\text{Hz}} \), \( \Delta f_{\text{FLL}} \sim 10 \text{kHz} \)

<table>
<thead>
<tr>
<th>( \Phi_{\text{max}} )</th>
<th>1 ( \Phi_0 )</th>
<th>100 ( \Phi_0 )</th>
<th>10,000 ( \Phi_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{\text{min}} )</td>
<td>18 bit</td>
<td>25 bit</td>
<td>31 bit</td>
</tr>
<tr>
<td>DNR</td>
<td>186 dB</td>
<td>226 dB</td>
<td>266 dB</td>
</tr>
</tbody>
</table>

high requirements on ADC performance
many possibilities to increase dynamic range...

... e.g. flux counting electronics, digital SQUIDs, SQIFs, SQUADs, SQUID cascades...

3 dc-SQUIDs with different input sensitivity
+ 3 FLL-electronics and 3 digitizer used

flux ramp modulation

application of sawtooth-shaped current signal results in periodic SQUID characteristics

flux ramp modulation

application of sawtooth-shaped current signal results in periodic SQUID characteristics

phase of SQUID characteristic linear measure of input signal
dynamic range not limited by ADC resolution + range

experimental setup for proof-of-concept

C6XS116W, PTB Berlin
linearity and dynamic range

application of flux ramp with 1 MHz repetition rate and $4.2\Phi_0$ amplitude

measurement of input signal with amplitudes between $100 \text{ m}\Phi_0$ and $2500 \Phi_0$
linearity and dynamic range

application of flux ramp with 1 MHz repetition rate and 4.2Φ₀ amplitude

\[
20 \cdot \log \left( \frac{2500 \Phi_0}{3 \frac{\mu \Phi_0}{\sqrt{\text{Hz}}} \cdot \sqrt{500 \text{kHz} \cdot 6.6}} \right) = 105 \text{dB} \quad \Rightarrow \quad \text{17.4 bit ADC}
\]

\[
20 \cdot \log \left( \frac{2500 \Phi_0}{3 \frac{\mu \Phi_0}{\sqrt{\text{Hz}}} \cdot \sqrt{10 \text{Hz} \cdot 6.6}} \right) = 152 \text{dB} \quad \Rightarrow \quad \text{25.3 bit ADC}
\]

measurement performed with \textbf{14 bit ADC}

measurement of input signal with amplitudes between \textbf{100 mΦ₀ and 2500 Φ₀}
frequency-division multiplexing capability
frequency-division multiplexing capability
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frequency-division multiplexing capability
proof-of-concept: HDFRMux1

flux ramp modulation based four-channel dc-SQUID multiplexer
proof-of-concept: HDFRMux1

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flux ramp modulation based four-channel dc-SQUID multiplexer

$M_{\text{mod}}$ adjusted by varying overlap between SQUID washer and modulation coil
HDFRMux1 – modulation demonstration

1 kHz flux ramp repetition rate

different carrier frequencies clearly visible in spectrum of output signal
performance of HDFRMux1 – multiplexing capability

different signal on SQUID inputs, 250kHz flux ramp repetition rate

successful demonstration of flux ramp modulation based dc-SQUID multiplexing technique
performance of HDFRMux1 – crosstalk

10 kHz sinusoidal signal in SQ2, 250 kHz flux ramp repetition rate

measured crosstalk between channels < 0.5 %
summary and outlook

novel dc-SQUID readout technique
- ‘infinitely’ large dynamic range
- no slew rate limitations
- MHz frequency domain multiplexing capability

what’s next?
- ‘optimized’ devices
- Further reduce crosstalk in FRM-muxing
- readout noise optimization (preamplifier)
- dedicated readout electronics (FPGA based)
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thank you for your attention!