Superconducting Quantum Circuits

Juan José García Ripoll, Spanish National Research Council
The OSA Quantum Computing and Communication Technical Group Welcomes You!

SUPERCONDUCTING QUANTUM CIRCUITS

2 July 2020 • 10:00 EDT
Technical Group Leadership 2020

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Technical Group at a Glance

• Focus
  • Theoretical and experimental aspects of quantum computing
  • Quantum communication systems - Cryptography
  • Generation, detection and applications of non-classical light
  • Quantum measurement and quantum control

• Mission
  • To maximize the exchange of information and the creation of networking opportunities for our community
  • Webinars, technical events (workshops, tutorials, poster sessions), outreach activities
  • Interested in presenting your research? Have ideas for TG events? Contact us at TGactivities@osa.org.

• Find us here
  • Website: www.osa.org/OC
  • Facebook: https://www.facebook.com/groups/OSAQuantumCC/
Today’s Webinar

Superconducting Quantum Circuits

Dr. Juan José García-Ripoll

Leader of the Quantum Information and Foundations Group at CSIC
jj.garcia.ripoll@csic.es

Speaker’s Short Bio:

Juan José García Ripoll finished his PhD in Optics at Univ. Complutense de Madrid, while working at Univ. Castilla La Mancha on Bose-Einstein condensates and nonlinear Optics. He then moved to Munich with Ignacio Cirac, where he developed key contributions in the fields of trapped-ion quantum computing and helped starting the field of quantum simulation with ultracold atoms. He is the coordinator of the CSIC Platform on Quantum Technologies and the Spanish Network of Quantum Information and Quantum Technologies.
Superconducting Quantum Circuits

Juan José García Ripoll
Institute of Fundamental Physics
<table>
<thead>
<tr>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>$10^4$</th>
<th>$10^5$</th>
<th>$10^{25}$</th>
</tr>
</thead>
</table>

[Chemical structure and diagram elements related to light and ion trapping.]
Why?
Computation

53 qubits
100’s operations
Simulation
New physical possibilities

Relative interaction speed

Observation speed

$\alpha_{SB} = 1$

$\alpha_{SB} = 1/2$

$Z_0 = 70 \Omega$

$Z_0 = 50 \Omega$

Experimental


Martin V. Gustafsson et al, Science (2014)
<table>
<thead>
<tr>
<th>Frequency</th>
<th>Temperature</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{15}$ Hz</td>
<td>50.000 K</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>300 THz</td>
<td>15.000 K</td>
<td>Near infrared</td>
</tr>
<tr>
<td>1 THz</td>
<td>50 K</td>
<td>High-energy microwaves</td>
</tr>
<tr>
<td>1-20 GHz</td>
<td>50 mK – 1 K</td>
<td>Microwaves</td>
</tr>
</tbody>
</table>

![Graph](image_url)
Figure 1. Heike Kamerlingh Onnes (right) and Gerrit Flim, his chief technician, at the helium liquefier in Kamerlingh Onnes’s Leiden laboratory, circa 1911.
Aluminum (Al)

Type I superconductor

\[ T_c = 1.2 \text{ K} \]
\[ \Delta = 0.34 \text{ meV} \sim 2\pi \times 82 \text{ GHz} \ (\sim 7/2k_B T_c) \]

Niobium (Nb)

Type II superconductor

\[ T_c = 9.26 \text{ K} \]
\[ \Delta = 30.4 \text{ meV} \sim 2\pi \times 735 \text{ GHz} \]

YBaCuO

Preliminary circuits for military RF applications

*A. Volodin et al EPL 58 (4), p. 582 (2002)*
Low temperature Physics

Typical energy scales
Microwaves, 1-30 GHz

Associated temperatures
T \sim 0.05 - 1.5 \text{ K}

Work in dilution refrigerators
T \sim 11-20 \text{ mK}

Superconductors:
Al, Nb, ...

Size, heating? Interface to outer world?
Amplification & detection? ...
Zero-mode LC resonator

\[ \omega = \frac{1}{\sqrt{LC}} \]

Waveguide:

Confined electromagnetic field among two or more conducting plates, on an isolating substrate.
"Equivalent circuit"

Note:

\[
\frac{d\phi_i}{dt} = V_i
\]
“Equivalent circuit”

\[ \frac{d\phi_i}{dt} = V_i \]
Normal mode description

\[ H = \sum_k \hbar \omega_k a_k^+ a_k \]

Dispersion relation

\[ \omega_k \approx m^{-1} k^2 + \omega_0 \]

EM modes

\[ u_k(x, y, z) \]
Qubits
Hey, resonator:
You want to be a qubit?
Be nonlinear!

#QuantumHaiku

J. Preskill @preskill
\[ E_n = \hbar \omega n \]
\[ E_n = \hbar \omega n - \alpha n(n - 1) \]

Harmonic oscillator

\[ E_n = \hbar \omega n \]
Transmon Qubit

$E_n = \hbar \omega n - \alpha n(n - 1)$
(tuneable) Transmon Qubit

$E_n = \hbar \omega n - \alpha n(n - 1)$
Artificial atoms zoo

Charge qubit
Phase qubit
3 junction flux qubit
Transmon qubit
Fluxonium
Capacitively shunted flux qubit...
Circuit QED
Spontaneous emission

\[ |e, 0\rangle \quad |g, \phi(x)\rangle \]
What theoreticians see

$|e, 0\rangle$

$\gamma_l$ $|g, \phi(x)\rangle$

What experimentalists do
\[ f(t) \xrightarrow{i(t)} f^*i \]
\[ f(t) \xrightarrow{90^\circ} f_0(t) \]
\[ f_0(t) \xrightarrow{\hat{X}_\omega(t)} \]
\[ f_90(t) \xrightarrow{\hat{P}_\omega(t)} \]

A. Sharafiev et al., arXiv:2001.09737
Strong coupling

\[ H = \frac{\Delta}{2} \sigma^z + \frac{\epsilon}{2} \sigma^x + \omega a^+ a + g (\sigma^+ a + \sigma^- a^+) \]

Jaynes-Cummings model

Ultra-strong coupling

Great impedance match!

Superconducting qubits

© UCSB / Google Lab
Quantum filters
Quantum filters
1 qubit operations
Measurements

Input

Output

Frequency
Measurements

|0\rangle |0\rangle

Frequency

Input

Output
Measurements

|1⟩

Input

Output

Frequency
Measurements
Measurements

|0⟩  | 1⟩
Measurements

\[ |0\rangle \quad |1\rangle \quad \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) \]
Quantum gates: e.g. “swap”

\[
\begin{array}{c|c|c}
\mid 1,0\rangle & \mid 1,0\rangle \\
\mid 0,1\rangle & \mid 0,1\rangle & \mid 0,1\rangle \\
\end{array}
\]
Hard mathematical problems

Quantum matter models

http://avaqus.eu
Quantum Local Area Network (QuLAN)

Distributed superconducting quantum computers

Light ↔ μwave

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http://quinfog.hbar.es

http://www.csic.es