Simulation of QPSJ-based Parametric Amplification

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Josephson junctions and quantum phase-slip junctions [1]

- A Josephson junction is a device with two superconducting electrodes separated by an insulating layer.
- Cooper pairs can tunnel between the two electrodes through the insulating layer.
- This allows for a supercurrent to flow between the two electrodes with zero voltage.

- The QPSJ is the exact dual to the Josephson junction. It consists of two insulating dielectrics separated by a thin superconducting nanowire.
- The two dielectrics contain flux-quanta, or fluxons.
- Whereas the Josephson junction has Cooper pairs tunneling between a separating dielectric barrier, the QPSJ has fluxons tunneling across the superconducting nanowire.
Wave-mixing and degeneracy in parametric amplifiers [2]

- Three-wave mixing: \( \omega_p = \omega_s + \omega_i \)
  - One photon in pump is converted to one photon in idler and one photon in signal
- Four-wave mixing: \( 2\omega_p = \omega_s + \omega_i \)
  - Two photons in pump are converted to one photon in idler and one photon in signal
- Degenerate: Two or more tones are on same spatial port
- Non-degenerate: All tones are each on separate ports
Traveling-wave parametric amplifier [3]

- Traveling-wave parametric amplifiers are designed as microwave transmission lines enabling the mixing of propagating microwaves via a nonlinear parameter, such as the resonator’s inductance or capacitance.
- The TWPA shown here is based on LC-ladder transmission lines.
- The pump and signal are input in the same line.
- The signal is amplified as it travels down the circuit.
Due to the high number of repeating nodes in the circuit, a Python program is used to create the circuit files. Each node consists of a JJ, a parallel inductor, and a capacitor connected to ground each side. Each node also has its own DC bias line, which is coupled to the JJs' parallel inductor. The bias current is the same across all nodes. The pump and the signal are input into the circuit via the same current source. The circuit is terminated by a 50 Ω impedance.
The output was taken all nodes of a 500 node JTWPA.

The signal tone was input at 0.1µA at 7.2 GHz and the pump tone was input at 1.97µA at 12 GHz. The idler tone is 4.8 GHz, the signal tone is 7.2 GHz, and the pump tone is 12 GHz.

In a TWPA, the signal and pump are input along the same line, and thus the wave-form here is bigger than the signal tone (0.1µA signal amplitude and 1.97µA amplitude).

The results show amplification of the signal tone and the creation of an idler tone at 4.8 GHz, demonstrating three-wave mixing.
QPSJ-based TWPA node in WRspice

- A similar Python program used to produce the JTWPA circuit file is used for the QPSJ-based TWPA.
- Each node consists of a center inductor, with two QPSJs on each side connected to ground.
- If the bias voltage is being tested, a DC voltage source is added between each QPSJ and ground.
QPSJ-based TWPA spectrum

- The output here was taken at all nodes of a 500 node QPSJ-based TWPA.
- The signal tone was input at 0.1 μV at 7.2 GHz and the pump tone was input at 1.97 μV at 12 GHz. Just like the JTWPA, with a TWPA the signal and pump are input along the same line, and thus the waveform here is bigger than the signal tone (0.1 μV signal amplitude and 1.97 μV amplitude).
- The results show amplification of the signal tone and the creation of an idler tone at 16.8 GHz, demonstrating four-wave mixing.
The bias voltage was swept from -5 to 5μV.

A Fourier transform was performed on the output voltage to get the signal tone's amplitude.

Similar to the JTWPA, the bias voltage is crucial to whether the amplifier operates in the three-wave or four-wave regime.
The critical voltage of all QPSJs in the circuit was swept from 0 to 20μV.
At values below about 3μV, the critical voltage was found to be too low for the circuit to operate properly, as the simulations gave illegible results.
Past the value, we started seeing numerous peaks in the signal gain.
• The node count was increased from 500 to 600 in WRspice.
• For each simulation run, the voltage output at the 100th to last node was recorded, and the signal tone's amplitude was subsequently found via a Fourier transform.
• The signal tone's gain increased from 500 to about 515, but afterwards it decreases until about 580 nodes.
Future work [4]

• Simulation of circulators (useful for lumped-end amplifier simulations)

• There is literature which introduces circulators using JJ/QPSJs which could be implemented in WRspice.
• Josephson ring modulators (JRM)s and Josephson parametric converters (JPC)s

• There are still other types of quantum parametric circuits that could be simulated, the biggest being the JPC, which could be implemented similarly to our current amplifiers.

Future work [5]
Future work [6, 7]

• Variable resonators
• Some of the literature do not use one type of resonator (e.g. quarter wave) and instead combine different types
• Simulating these circuits would require more careful implementation our resonant structures in WRspice
References


