QuantumPro: An Integrated Workflow for the Design of Superconducting Qubits using PathWave Advanced Design System (ADS)

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***Abstract*—We present current developments in Keysight Pathwave Quantum Technology to analyze superconducting quantum circuits. Particularly, Pathwave ADS and its most recent Electromagnetic (EM) simulation package, QuantumPro, enable investigating nonlinear effects such as cavity quantum electrodynamics and automated computation of the quantum parameters including the qubit anharmonicities and cross-Kerr strengths. Under the low power assumption, superconducting qubits are treated as linear lumped circuit elements in the EM simulation environment. To study the nonlinear regime, Pathwave ADS provides a co-simulation approach that enables combining the linear frequency response from the full-wave EM simulation with the nonlinear circuit analysis in the ADS schematic. To assess the accuracy of Pathwave ADS, we compare the results to the two coupled transmons showcase example from the IBM Quantum Qiskit Metal framework. In addition, we also demonstrate power-dependent nonlinear bending of the frequency response by sweeping the input power into the superconducting circuits in Pathwave ADS.**

***Index Terms*—Superconducting qubits, Pathwave ADS, QuantumPro, EM simulation**

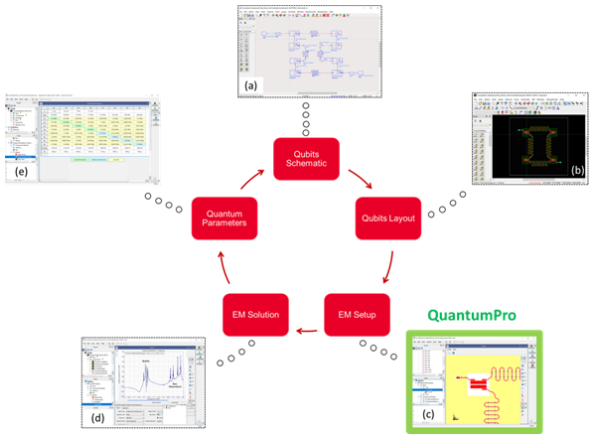


Fig. 1: The iterative workflow in Pathwave ADS where users create the schematic/layout, simulate the design and automatically extract quantum parameters in QuantumPro, and revisit the design for optimal results.

I. Introduction

Superconducting quantum circuits have recently shown great potential in quantum computing research thanks to their robustness and scalability. Especially, due to the low operating temperature the superconducting qubits can be manufactured at a macroscopic level [1]. That enables researchers and engineers to use circuit design and simulation tools such as IBM Quantum Qiskit Metal [2] to analyze advanced superconducting circuits. While Qiskit Metal is based on an energy participation analysis (EPR) [3], Pathwave Advanced Design System (ADS) allows users to carry out both eigenmode and frequency domain analyses.

We introduce the quantum circuit analysis within Pathwave ADS and its QuantumPro package. QuantumPro is built specifically to analyze superconducting qubits. Users may construct the superconducting circuit/layout in Pathwave ADS and export the geometry for simulation in QuantumPro as shown in Fig. 1. Then, QuantumPro calculates the quantum parameters based on the EM simulation. As the figure suggests, users may revisit previous steps to optimize the circuit performance. The integrated workflow that Pathwave ADS provides is the first in the electronic design automation (EDA) industry for the design of superconducting qubits.

To showcase the accurate modeling capability of Pathwave ADS, we replicate the two coupled transmons example presented in Qiskit Metal documentation. Furthermore, we discuss how to incorporate nonlinear components in ADS

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simulations to explore the power-dependent circuit response.

II. Two Coupled Transmons

We explore a showcase example of two coupled transmon qubits of IBM Quantum Qiskit Metal [2]. We reproduce this example in QuantumPro for both the eigenmode analysis in Energy Participation Analysis (EPR) and for the frequency domain (FD) analysis in Full EM Analysis to derive the quantum parameters matrix χ, as shown in Fig. 3

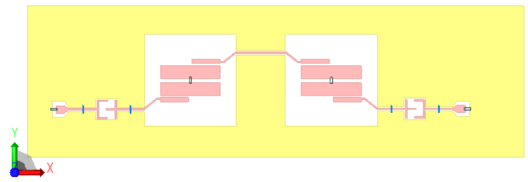


Fig. 2: Two coupled transmon qubits in QuantumPro. The junction inductance for the left (right) qubit is 13 nH (8 nH).

The two transmons have different junction inductances, 13 nH for the qubit on the left and 8 nH for the qubit on the right, leading to two distinct resonant frequencies. Since the two transmons are directly coupled, a nonlinear effect manifested by a non-zero cross-Kerr strength results in a shift in their resonances. The simulation results in comparison to the Qiskit model are summarized in Tab. I. The resonant frequencies for the transmon qubits are in excellent agreement between Qiskit Metal and QuantumPro.

(a) Eigenmode (EPR)

	Q1	Q2
L	13 nH	9 nH
Freq	5.72 GHz	6.87 GHz
Q1	324 MHz	0.657 MHz
Q2	0.657 MHz	324 MHz

(b) Frequency Domain

	Q1	Q2
L	13 nH	9 nH
Freq	5.64 GHz	6.75 GHz
Q1	316 MHz	
Q2		314 MHz

Qubit Anharmonicity	Cross-Kerr

Fig. 3: The quantum parameters matrix χ derived using QuantumPro using both Eigenmode and Frequency domain solvers yield very similar results.

TABLE I: Simulation results for the Two coupled transmons in Qiskit Metal and in QuantumPro (QPro).

	Qiskit Metal [2]	QPro (EPR)	QPro (FD)
Qubit 1 Mode	5.32 GHz	5.4 GHz	5.32 GHz
Qubit 2 Mode	6.46 GHz	6.54 GHz	6.43 GHz
Qubit 1 $\lvert\alpha_q\rvert$	312 MHz	324 MHz	316 MHz
Qubit 2 $\lvert\alpha_q\rvert$	311 MHz	324 MHz	314 MHz
Cross-Kerr χ	0.46 MHz	0.66 MHz	N/A

III. Power Dependent Nonlinear Bending

In this section, we discuss how to obtain the frequency responses of superconducting quantum circuits using a nonlinear Josephson junction in PathWave ADS. The nonlinear analysis requires two steps. First, we carry out an EM simulation for the one-qubit-one-resonator example in Fig. 4 over the frequency range (4-10 GHz). We then export the scattering parameters to the ADS schematic that contains the Josephson junction and the harmonic balance analysis as shown in Fig. 4.

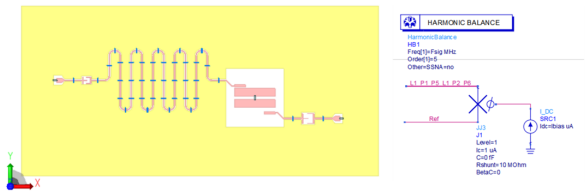


Fig. 4: The circuit model of the one-qubit-one-resonator example (left). The ADS schematic with the Josephson junction and the harmonic balance analysis (right).

The transmission spectrum of the qubit and resonator is shown on the left side of Fig. 5. The qubit resonance is near 6.2 GHz while the resonator resonance is near 8.1 GHz. In PathWave ADS, we sweep the input power from -180 dBm to -160 dBm and obtained a series of transmission curves on the right side of Fig. 5. As expected, the resonator peak shifts gradually as the input power increases, and the peak becomes distorted on one side, which is known as nonlinear bending.

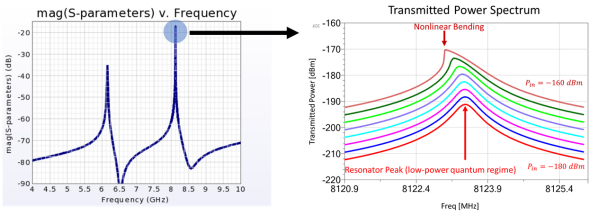


Fig. 5: The linear transmission response of the quantum circuit (left). Using the Pathwave ADS harmonic balance, the nonlinear bending of the resonator peak is observed (right).

IV. Conclusions

In this work, we introduced QuantumPro, an EM simulation package to analyze superconducting quantum circuits. QuantumPro provides automated quantum parameter extraction capability in the quantum circuit design workflow for the first time in Pathwave ADS. We presented the two transmons example to showcase its effectiveness in quantum circuit analysis. The results from QuantumPro had good agreement with those from the Qiskit Metal framework. Furthermore, we showed how users can export the circuit response from QuantumPro to an ADS schematic to analyze the nonlinear power-dependent effects in quantum circuits.

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