

Designing for Superconducting Qubit Circuits

Using PathWave ADS to design basic quantum computing circuits

Overview

The advantage of quantum computing stems from its unique exponential scaling in computational capability with the increased number of quantum bits (qubits), which enables quantum computers to tackle problems far beyond the reach of classical ones. In recent years, researchers have demonstrated various quantum computing platforms as candidates to scale up quantum computing operations. One of these platforms, the superconducting qubits, which operate at milli-Kelvin temperature, has shown great promise for their robustness, scalability, and manufacturability.

Qubits can be envisioned as an almost isolated two-level quantum system. Unlike classical computing bits with two states (zero and one), qubits form superposition states between the two levels such that a single qubit has two states, and therefore n qubits have 2^n states; thus, the powerful exponential growth for quantum computing.

The essential circuit element of superconducting qubits is the Josephson junction, which is formed by sandwiching a thin insulator layer between two superconducting electrodes. The Josephson junction, with its nonlinear inductance, makes up the artificial atom (two-level systems) that can be used as a basis for quantum computing.

Superconducting qubit circuits usually consist of a network of qubits and meander line resonators. Researchers have been investing their effort in expanding superconducting qubit circuits to contain hundreds of elements for more advanced computation. PathWave Advanced Design System (ADS) provides the necessary tools to design and simulate superconducting qubits from basic to broader quantum application circuits.

In this application note, we demonstrate how users can build, analyze, and create fabrication blueprints of simple quantum computing circuits. PathWave ADS has various quantum components to create quantum circuit schematics and layouts. The layouts subsequently are turned into a full 3D geometry for full-wave RF simulations. Then, users can generate circuit fabrication files in GDS format for fabrication.

Introduction to Superconducting Qubits

Superconducting qubits play an essential role as the primary building block of quantum processing units. Each superconducting qubit can be thought of as an artificial atom with quantized energy levels that responds to a microwave drive tone as a neutral atom would to a photon. The Josephson effect, a mechanism behind the formation of a qubit, can be observed at a milli-kelvin temperature for superconductor-insulator-superconductor junctions. These superconducting qubits typically operate at the order of gigahertz frequencies. The design of these superconducting qubits follows a typical microwave circuit design process. The quantum microwave circuit usually consists of coplanar waveguide resonators coupled to qubits. The resonators are used for two purposes; to read out the state of the qubits and to make them talk to each other; in quantum language, that is called entanglement. From a microwave design perspective, the circuit will have many resonance frequencies corresponding to the resonators and the qubits [1, 2]. Qubits can be abstracted by their lumped inductances expected in the quantum regime at very low signal excitation [3, 4]. The chip design entails engineering the resonators and the qubits to land the different frequencies of the circuit to targeted values and adjusting the coupling between the resonators and qubits to meet certain quantum parameters. When the qubit changes its state, we will be able to see that on the microwave signal response of its associated readout resonator with a shift in its resonant frequency.

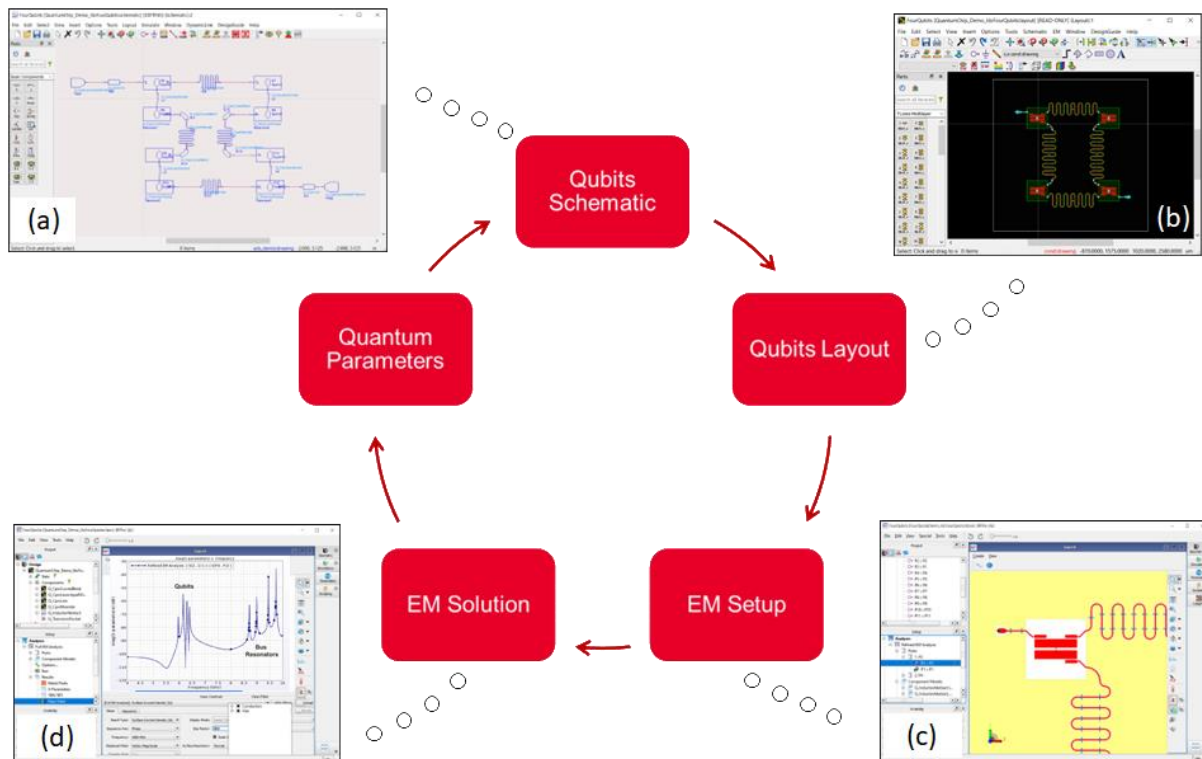


Figure 1. Design cycle of superconducting quantum circuits. (a) PathWave ADS Schematic view of the circuit. (b) PathWave ADS Layout view of the circuit. (c) The EM setup in RFpro. (d) The RF simulation results in the frequency domain.

PathWave ADS offers various quantum components at a circuit design level to design quantum computing circuits from scratch. The workflow is shown in Fig 1. Users start by creating a schematic as shown in Fig 1. (a), and simultaneously generate the layout in the layout view in Fig. 1 (b). After properly setting up the EM simulation, the users then export the model to RFPPro for full-wave simulation. Once the EM simulation is performed, the users obtain the frequency response of the circuit and proceed to extract the quantum parameters. The quantum parameters represent the unique properties of the quantum circuit components, which we will cover in more detail in another app note.

As Fig. 1 may further suggest, the design process of superconducting qubit circuits is iterative. After designing and carrying out the EM simulation, users may revisit the schematic, layout, or both to optimize the circuit performance. For instance, a meander line or a qubit can be further fine-tuned to a different frequency. Then the users may prepare a different run of EM simulation to reevaluate the circuit performance. This process may be repeated until the circuit shows desirable improvement. Once, the results come out satisfactorily, the design can be exported to a graphics layout output in a GDS format for cleanroom fabrication.

The challenging aspect of designing superconducting quantum circuits is the complexity of the electromagnetic simulation with the increased number of qubits. The circuit should support sets of distinct resonant frequencies for the qubits and the resonators. Although a qubit and a meander line resonator often have a large difference in their resonant frequencies in the dispersive regime, the frequency difference between two qubits or two resonators is much smaller and needs to be resolved with much finer frequency resolution. Moreover, tuning qubits and resonators and their coupling implies a repetitive cycle of electromagnetic simulation that significantly prolongs the design cycle and increases the computational cost. In that perspective, planar microwave circuits lend themselves to a very cost-effective electromagnetic simulation solution using the method of moments, which instead of solving for the electric field in the full volume, solves only for the currents on the metal surface, significantly cutting the computational cost. Planar quantum circuits can leverage the same benefits enabling faster design cycles for large quantum circuits.

In this app note, we demonstrate the design of a simple superconducting qubit circuit consisting of four transmon qubits, four meander-line coupling resonators, and other passive elements. Transmon qubits [4] and meander-line resonators [5] are some of the most commonly used elements in superconducting quantum processing units. We discuss how to ensure that the design achieves the resonant modes in more detail.

Quantum Layout Components

PathWave ADS has over a dozen quantum components to create advanced superconducting circuits. A transmon cross (**Q_TransmonCross**) and a transmon pocket (**Q_TransmonPocket**) are the qubits. The components, coplanar waveguide (CPW) lines (**Q_CpwLine**) and CPW meander lines (**Q_CpwMeander**) provide TEM transmission lines. The latter can be terminated in an open or short circuit to support a resonator mode, or in the context of the circuit in Fig. 2, serve as a bus meander-line resonator. The launchpad (**Q_CpwLaunchpadWirebond**) may be used as an excitation port in the EM simulation. In experiments, a thin wire can be bonded to the launchpad to provide an RF signal to the circuit.

Other components include commonly used components such as a bend (**Q_CpwCurvedBend**) and a coupler T (**Q_CpwCouplerT**). In PathWave ADS, apart from the Josephson junction circuit component (JJ2 and JJ3), all quantum components are passive. The active components are only used in the PathWave ADS circuit simulation (e.g. harmonic balance), which is discussed in detail in another app note.

In the schematic view, the users create quantum circuits by providing basic parameters and information on how each component is oriented and connected. Then, the layout is generated automatically based on the schematic. Quantum layout components are arranged in a way that meets the requirements specified by the user input in the schematic. For instance, the meander lines (**Q_CpwMeander**) maintain the user-defined offset between the start and end points while adjusting the length, width, and spacing of the meanders automatically to ensure spatial requirements are satisfied

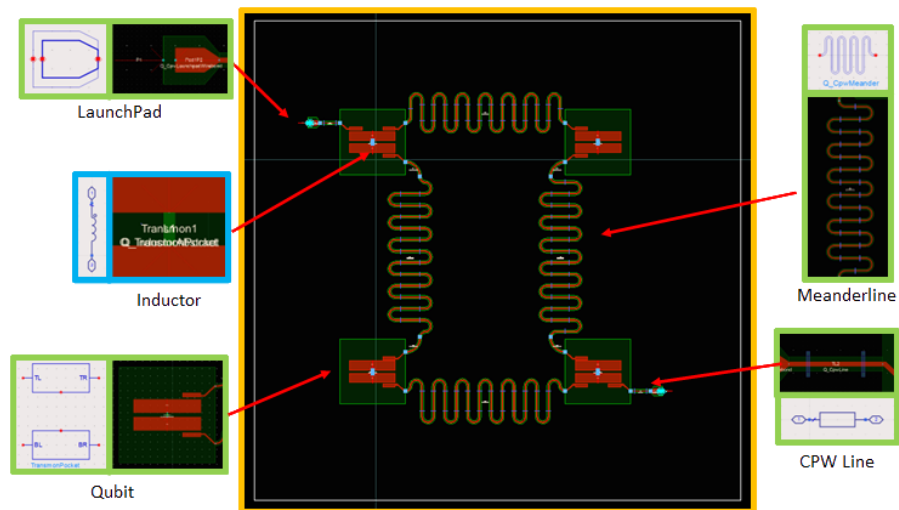


Figure 2. PathWave ADS Quantum components for superconducting circuits as shown above. Here, four transmon qubits and four meander line resonators form a four qubit four bus line network.

Quantum components such as CPW lines and CPW meander lines have periodically built-in airbridges over them. The airbridges are metallic parts that connect the outer ground planes over the center line to suppress the excitation of an unwanted high-order mode. This high-order mode, or a nonsymmetric “odd” mode, can be detrimental to the performance of the superconducting circuits. In implementing the airbridges, users may customize the dimensions and placement periodicity of the airbridges to ensure that excitation of the higher-order mode is significantly suppressed.

Lastly, for the four qubits and four meander lines example (Fig. 2), in layout designs and full-wave simulation, we assign perfect electric conductors to all quantum components to mimic the low-temperature conditions of the superconductors. In the next section, we provide detailed information on the frequency analysis of the quantum circuit.

EM Simulation

Before fabrication, it is imperative to analyze the circuit to make sure that a circuit would produce the desired frequency response in experiments. In this section, we detail how to carry out a full-wave EM simulation to analyze a superconducting circuit. As mentioned earlier, the superconducting qubits are highly nonlinear. Since the EM flow only supports linear analyses, the qubit junctions can be abstracted by their lumped inductances expected in the quantum regime at very low signal excitation.

In the layout view, circuit ports are identified across the circuit elements as shown in Fig. 3. There are two ports, Port 1 and Port 2, for the main input/output signal and four other ports across the qubit junctions. An example of the qubit junction port is shown in the top close-up view in the figure while an example of the input/output port is shown in the bottom close-up. In the schematic view, these ports are created by placing pins (e.g. P1, P2, P3, and P4 from the figure) across the transmon qubits and the launchpads, respectively.

A frequency response of the circuit requires a frequency sweep between Port 1 and Port 2. More advanced analyses such as quantum parameter extraction would require calculation involving the four additional qubit ports as well. In this app note, we will mostly focus on the two-port (input/output) analysis. As the RF signal is injected into Port 1 (or Port 2), the transmitted RF power can be detected at Port 2 (or Port 1). The transmission peaks near the resonant frequencies of the meander line resonators and the transmon qubits. The goal of this four-qubit design example is to set appropriate parameters to have distinct peaks for all four meander line resonators and four qubits.

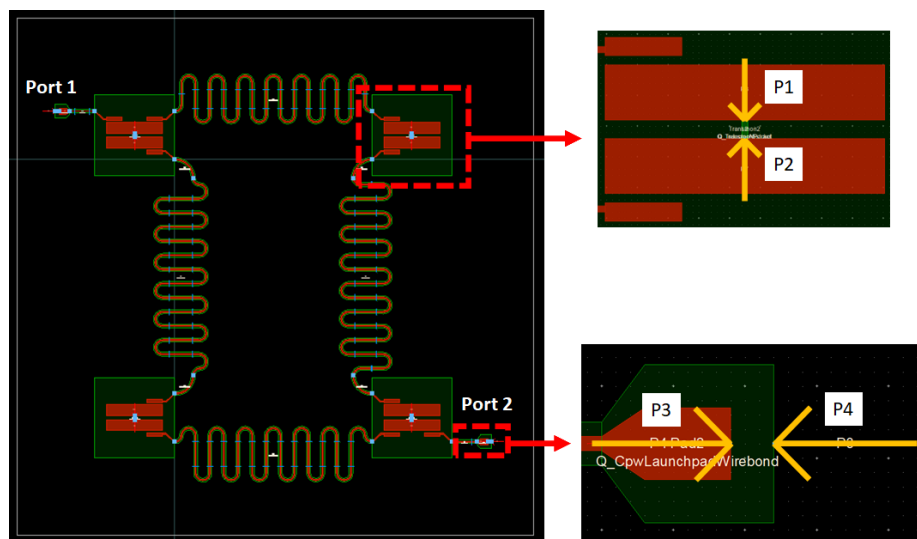


Figure 3. Port definition in the layout view. The transmon qubit is modeled as two charge islands with a lumped inductor placed between them. (Top) Pins P1 and P2 are placed across the transmon qubit to form a lumped port. An abstract inductor is placed between the pins. (Bottom) Pins P3 and P4 are placed on the launchpad and the ground plane to form an input/output port. Orange arrows and labels are added for clarity in the figure.

When the qubits' inductance is deactivated, it simulates the classical regime of high-power excitation, and only the peaks of the resonators will be visible. Conversely, incorporating the qubits' inductance represents the quantum regime of very low power excitation, allowing us to observe the resonances of both qubits and resonators [6]. It is noteworthy that switching the qubit "off" (classical) and then "on" (quantum ground state) causes a slight shift in frequency in the resonators' peaks, which is utilized to extract the quantum parameters.

Fig. 4 shows a transmon qubit with its junction represented as a lumped element with parallel capacitance and inductance. In PathWave ADS, we call this lumped element an abstract inductor (**Q_InductorAbstract**). Although the inductance is the primary attribute of interest of the qubits, users may also include the junction capacitance across the charge islands in the transmon. Therefore, the junction acts like a classical LC oscillator in the linear regime. For fabrication, PathWave ADS generates a layer devoted to the abstract inductor. The meander line resonators, shown as squiggly lines connecting qubits in Fig. 3, are transmission lines that are terminated open. Their resonant frequency is dictated mostly by their line length.

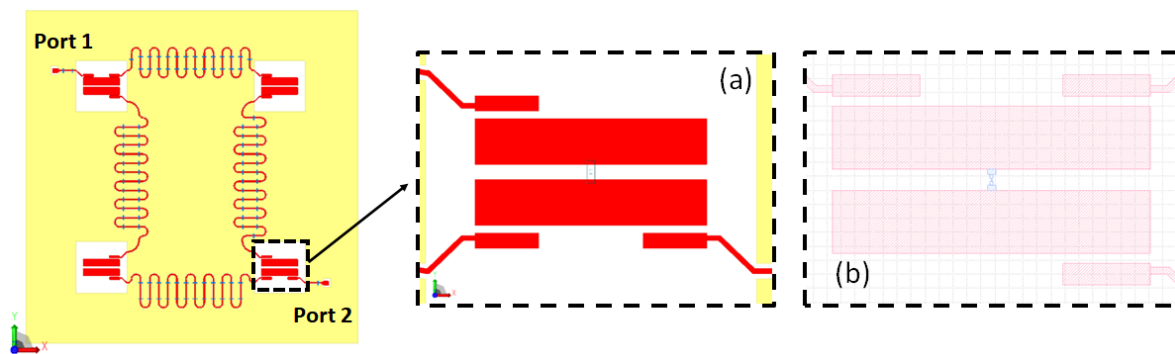


Figure 4. The qubits in an RFPro circuit model. (a) Abstract inductors are used as a lumped element to simulate the LC circuit. (b) A "placeholder" model for the abstract inductor across the qubit junction.

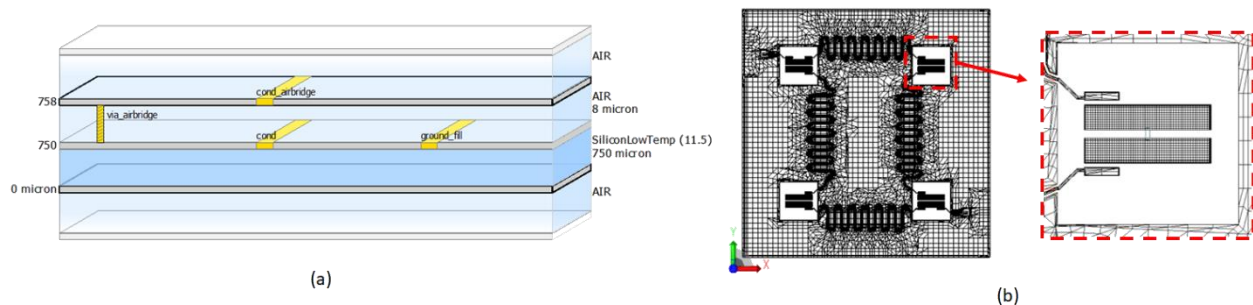


Figure 5. Two additional important steps for the EM Simulation (a) Setting up the substrate and the layers of the circuit. (b) Refining the final meshes for the circuit layout.

RFPPro has a full-wave Method of Moment (MoM) and Finite Element Method (FEM) solvers. The former focuses on solving for the current in the system with a given excitation voltage while the latter focuses on finding electromagnetic fields everywhere within the boundary. For these reasons, the computational time, and meshing schemes for the two methods may differ significantly with MoM computationally less costly as mentioned earlier. With a careful EM simulation setup, however, they both yield comparable simulation results.

Next, the layer and substrate properties need to be properly set. The substrate editor view of the circuit in Fig. 5 (a), shows the thickness and properties of all layers including the substrate. The substrate for the superconducting circuit also plays an important role in the frequency response of the circuit. A relatively thick silicon wafer ($> 100 \mu\text{m}$) is commonly used to fabricate superconducting circuits and its dielectric properties would impact the resonant frequencies of the circuit elements. For this example, we used a high-density silicon wafer with a dielectric constant of 11.5 (at low temperature). The airbridges for the CPW lines are also defined here as a separate layer.

After the substrate and layers are set up properly, users may customize the meshing of the model as shown in Fig. 5 (b). For improved accuracy, it is important to set the mesh parameters sufficiently small. However, a high mesh density increases the number of unknowns in the EM solution, leading to an increase in computational complexity. Therefore, it suffices to make the mesh density high near important features (e.g. center conductors and transmons), while keeping the ground plane coarsely meshed. RFPPro allows users to customize the mesh density for such critical components in the model.

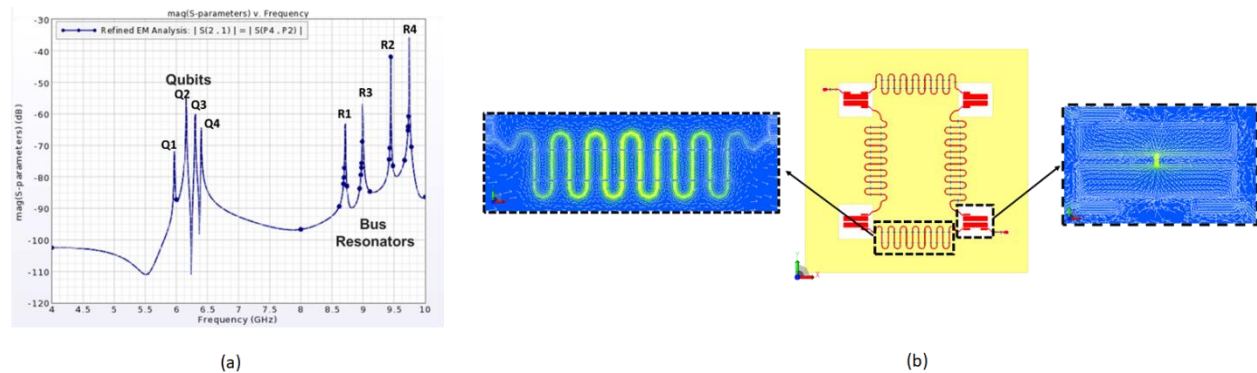


Figure 6. (a) The frequency sweep results for the four qubit four bus line quantum circuit. The eight distinct peaks correspond to the qubit and meander line resonances. (b) The strong current distribution in the circuit in a meander line (left) or a qubit (right) under a resonant condition.

Once the mesh density is properly set up, users may carry out a full frequency sweep analysis. The results of a frequency analysis are shown in Fig. 6. The design goal is to ensure the qubits and resonators support distinct modes. The transmission spectrum between the input/output ports, represented as S_{21} , reveals that this design goal is met: the plot in Fig. 6 (a) has eight peaks. The first set of peaks between 6 GHz and 6.5 GHz corresponds to the qubit resonance modes while the second set between 8.5 GHz and 10 GHz corresponds to the meander line resonance modes.

In case the eight peaks are not clearly resolved in the transmission frequency response, users may wish to revisit the design as we discussed in the introduction. The issue of peaks not being resolved is most likely due to the resonance modes overlapping. As the qubit resonances and meander line resonances are relatively far apart ($> 1 \text{ GHz}$), overlapping of a qubit mode and a meander line mode is unlikely.

However, interference of resonances between a qubit and a qubit (or between a meander line and a meander line) is a good place to start investigating.

The main tuning parameters for the transmon qubits are their junction inductance and capacitance. As the oscillation frequency of an LC circuit ($\omega_o = \frac{1}{\sqrt{LC}}$) suggests, when the junction inductance increases (decreases), the oscillation frequency would decrease (increase). As for the meander lines, their resonances mostly depend on their total lengths. As the total length increases (decreases), the resonant frequency goes down (up). Users may change these parameters manually and repeat the EM simulation or carry out a parametric sweep.

Furthermore, users may visualize the current distributions (or electromagnetic field patterns) after the MoM (FEM) simulation. Fig. 6 (b) shows the current distribution in a meander line (R2) and a transmon qubit (Q3) under resonance. The qubit is resonant at around 9 GHz and the meander line is resonant at 6.3 GHz. As the current distribution of the meander line suggests, the current forms a standing wave current that has a very small magnitude at the ends, forming the nodes while the current distribution is strong near the middle (antinode).

Lastly, we will only briefly touch on the topic of quantum parameter extraction from the frequency domain response in this app note [6, 7]. The quantum parameters such as qubit anharmonicity (α_q) and cross-Kerr (χ) represent important characteristics of quantum components. The qubit anharmonicity ($\alpha_q = -\frac{e^2}{2C}$) describes the deviation of the qubit's energy levels from those of an ideal harmonic oscillator, and it depends on the total capacitance (C) across the qubit junction at resonance. This total capacitance is obtained from the reflection coefficient at the qubit port at the resonant frequency.

The cross-Kerr between a qubit and a resonator is defined as $\chi = \frac{2g^2\alpha_q}{\Delta(\Delta+\alpha_q)}$. Here, when the junction inductance and capacitance are included across the transmon qubit in the qubit port admittance analysis, there is a frequency shift in the resonance conditions compared to when they are excluded. This frequency shift, known as a dispersive shift ($= \frac{g^2}{\Delta}$), allows for determining the parameters, g , the qubit-resonator coupling constant, and Δ , the detuning -- the difference in qubit and meander line resonant frequencies. The quasi-static method and eigenmode method can also offer alternative ways to calculate the quantum parameters. A comprehensive review of the methods will be detailed in another app note.

Overall, the linear EM flow can be utilized to predict accurately the frequency response of superconducting qubits. The linear analysis of the circuit provides powerful guidance under low-power approximation in the quantum regime. It will further help users to drill down on the design and produce the desired results in real experiments.

Exporting GDS File

After a successful EM simulation, the final step is to export the design layout to a GDS file. The GDS format is an industry-standard for layout fabrication, which foundries often will require to manufacture. While previous versions of PathWave ADS already support the GDS layout export feature for classical circuits, PathWave ADS allows for complicated and advanced quantum circuit designs. For instance, the final GDS design for the four-qubit example is shown in Fig. 7.

The design contains several layers. Firstly, **Boundary** defines the outermost edges of the circuit layout. It is usually a rectangle drawn around the circuit and all circuit elements lie within this boundary. The **Conductor** layer has all the traces for the main conductors that carry the signal current. It includes the center conductors of the CPW lines, the charge islands, the pads of the transmon qubits, and the launch pads. The **Ground-fill** layer is a metal plane that fills up the area between the **Boundary** and the Conductor layers. There is a layer called **Keep-out** that dictates the separation between Conductor and Ground-fill layers.

As discussed extensively in the EM simulation section, the schematic, layout, and EM model for this superconducting circuit example uses the lumped LC elements for the superconducting qubits. When the GDS file is generated, a separate layer is created for these abstract inductors. The Inductor layer as shown in Fig. 7, however, is not used in manufacturing. Rather, it serves as a placeholder for the Josephson junctions in the layout view. Airbridges consist of two parts: vias and conductors. The vias of the airbridges contact the outer ground planes and the conductor connect the vias over the center conductors. The vias and conductors are placed on different layers, the Airbridge Conductor layer and the Airbridge Via layer, respectively.

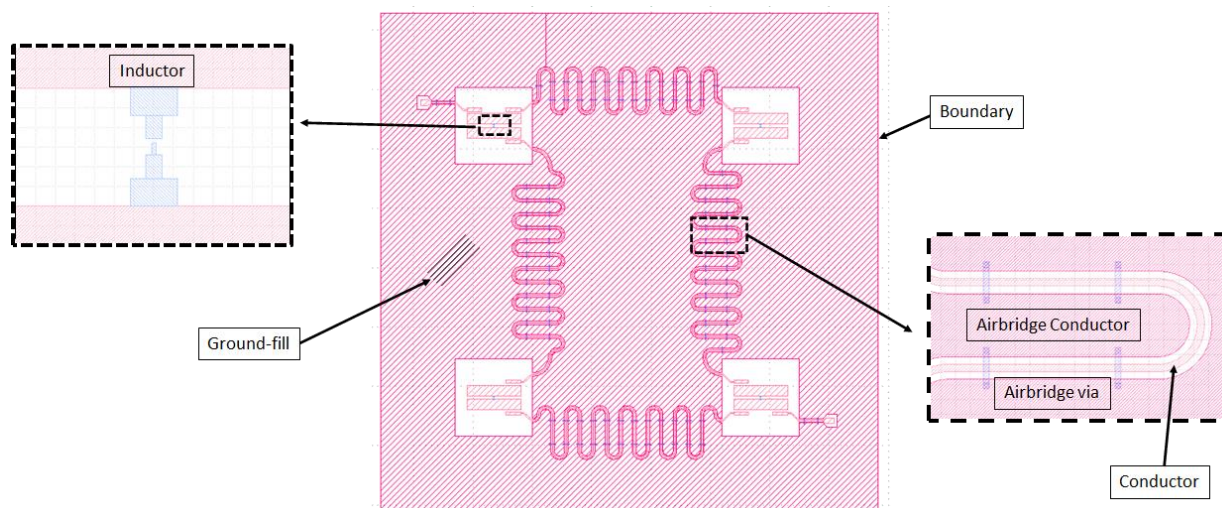


Figure 7. The GDS layout contains several layers for the quantum components. The quantum components such as inductors across qubits and airbridges are placed on separate layers.

In summary, PathWave ADS provides users with flexible tools and simulation methods to create advanced superconducting qubit circuits from initial schematic design to the generation of fabrication blueprints. This streamlined design flow, coupled with high accuracy, enables researchers in the field of quantum computing to create complex circuits with multiple quantum components. By offering a robust design and simulation experience, PathWave ADS can support the efforts of quantum computing researchers to develop increasingly sophisticated circuits.

Conclusions

PathWave ADS empowers quantum hardware engineers with an integrated workflow for faster development of quantum chips using a cost-effective electromagnetic simulation solution through the method of moments, which instead of solving for the electric field in the full volume, solves only for the currents on the metal surface, significantly cutting the computational cost.

In this application note, we demonstrated various features in PathWave ADS that allow for designing accurate superconducting quantum circuits from scratch. First, we introduced how to build quantum circuits using the quantum layout library, then we introduced the electromagnetic setup and the iterative process for tuning the superconducting qubits. A four qubits circuit was used in this demonstration. We also briefly discussed the quantum parameter extraction. Finally, we visited how the final circuit design is exported to a blueprint file in the GDS format for fabrication

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