EMERGING TECH CONFERENCE – Edge Intelligence

Volume 01, 2022, Page 188 – 191

Proceedings of Emerging Tech Conference:
Edge Intelligence 2022

Modeling of superconductive circuits for quantum computers

Konstantinos Nikellis*, Stefanos Stefanou and Yiannis Moisiadis

Ansys, Hellas, I. Apostolopoulou 26A, 15231 Chalandri, Athens, Greece

kostas.nikellis@ansys.com

Abstract

Superconductive silicon is one of the most promising technologies for implementing practical quantum computers. EDA vendors can assist in the quantum hardware designers' endeavors by providing solutions that can lead to designs of increased qubit quality. This technical report presents a new modeling engine that is able to model tens to hundreds of physical qubits capturing all coupling and crosstalk between them, thus providing the quantum hardware designers with vital information on the quality of their designs.

1. Introduction

In 1982, Richard Feynman, a theoretical physicist and Nobel Prize winner, introduced the initial concept of a quantum computer. Today, companies like Google, Amazon, Microsoft, IBM, and D-Wave are working to bring Feynman's ambitious theories to life by designing quantum hardware processing units to address problems it would take a traditional computer years to solve (if ever). They're tackling cryptography, blockchain, chemistry, biology, financial modeling, and beyond. But while the so-called "quantum supremacy" (the ability of a quantum computer to solve problems a classical computer cannot) has been theoretically proven, a practical demonstration would require engineers to build quantum circuits of greater size than what has been achieved so far.

Yet the problem posed by this scale-up is that as the number of qubits and gates increases, so does the error rate; error that accumulates in a computation each time the circuit performs a gate operation. When too high, quantum computers lose their advantage over classical ones. The effort towards increasing the quality of the quantum hardware is continuous and Electronic Design Automation vendors, such as Ansys have an important role to play here.

2. Superconductive qubit technology

One of the most promising technologies for implementing quantum processor hardware is superconductive silicon circuits. As a solid-state material, they can be built with existing fabrication techniques, are low-cost and easy to scale. Furthermore, they offer longer coherence times and faster gate operations compared to other quantum hardware designs. This, however, comes at a cost. Such circuits must be cooled down to extremely low temperatures very close to zero Kelvin, for the materials to exhibit the superconductive behavior.

In quantum designs on superconductive silicon, the basic building block is the Josephson Junction (JJ). In radiofrequency integrated circuit (RFIC) chips, that role is played by transistors. In both situations, these fundamental building blocks are used to build gates that ultimately form qubits in quantum and bits in RFIC. JJs, are combined with superconductive loops to form qubit circuits. The metal paths form junctions and loops with dimensions of just a few nanometers. But while qubits only need a tiny piece of layout area, they must be combined with much larger circuits for various operations (e.g., control, coupling, measurement). The ideal electromagnetic modeling tool for superconductive hardware design will need to maintain both accuracy and efficiency for layouts ranging from several millimeters down to a few nanometers to be beneficial in all stages of superconductive quantum hardware design.

Traditional electromagnetic solvers struggle with this complexity and size of quantum systems, so simulation providers need to step up their capacity to meet the moment.

2.1 Electromagnetic modeling of quantum circuits

Superconductors are not new, exotic materials but rather common metals like niobium or aluminum. Once these metals are cooled down to a few millikelvin, a portion of their electrons do not flow as they normally would. Instead, they form cooper-pairs. This superconductive current flow results in new electromagnetic effects that need to be accurately modeled.

In terms of inductance, this results into the appearance of an additional inductance term, called “kinetic inductance”. For a segment with length (l), cross-section (A) in a superconductive material with London penetration depth (λ) and conductivity (σ), the kinetic inductance (Lk) and superconductive electrical resistance (Rs) are given by the following equations:

$$L_k = \mu_o \lambda^2 \frac{l}{A} \quad , \quad R_s = \omega^2 \mu^2 \sigma \lambda^3 \tag{1}$$

Equations (1) reveal the actual challenge when modeling superconductors. The kinetic inductance, compared to the magnetic one, has no mutual component. It is not affected by any coupling; it is solely dependent on the dimensions of the superconductor and the temperature (that affects the London depth). The superconductive resistance is dependent on the square of the frequency and is proportional to the conductivity. In contrast, the ohmic resistance of conductors is dependent on the square root of the frequency and it is inversely proportional to the conductivity. These fundamental differences reveal the true challenge in superconductor modeling: one cannot simply calculate the Lk and Rs values and add them to the normal inductance and resistance of the material.

In Ansys, Inc. we have introduced a modified version of our hybrid Partial Element Equivalent Circuit – Random Walk (PEEC-RW) modeling engine (RaptorQu) that specifically targets superconductive circuits.

3. RaptorQu: A novel modeling approach

In any electromagnetic modeling tool, the optimal meshing needs to be small enough to properly approximate physical phenomena (e.g. the current distribution) but not excessively small so as to produce an unnecessary complex and inefficient model. For normal conductors, the mesh size depends on the skin depth (δ), which determines the electrical field penetration inside a conductor of conductivity (σ). The skin depth is frequency dependent therefore the mesh

generation is frequency driven. For superconductors this mechanism is not applicable because the current penetration inside a superconductor depends on the "London penetration depth" (λ):

$$\lambda_T = \frac{\lambda_{(0)}}{\sqrt{1-(T/T_c)^4}} \quad (2)$$

Where λ(0) is the penetration depth at 0K degrees and Tc the material's critical temperature.

This penetration depth is frequency independent and temperature dependent (T) and as a result it renders the typical meshing mechanism inapplicable. In RaptorQu we introduce an updated meshing algorithm that accepts either direct definition of the London penetration depth or calculates it from a temperature definition. In addition to that, since the value of (λ) is usually much smaller than (δ), the scaling of the mesh cells towards the center of a superconductor is more aggressive to maintain the efficiency of the engine.

In terms of modeling, the fundamental LR equivalent circuit of the PEEC method has been enhanced, with the addition of components that ensure that the broadband behavior of the superconductor's impedance matches the theoretically anticipated trend.

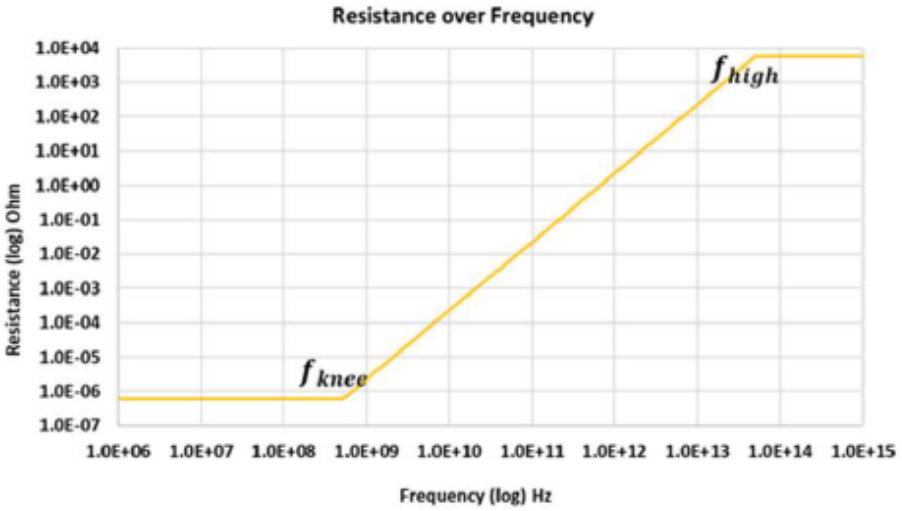

Figure 1: Resistance over frequency of the modified PEEC circuit.

3.1 Results

RaptorQu allows the users to fully exploit the speed and efficiency of the hybrid PEEC-RW methodology and cosimulate tens or even hundreds of physical qubits. Modeling of superconductive circuits of this scale was previously only possible through segmenting and disregarding any potential coupling between parts of the circuit.

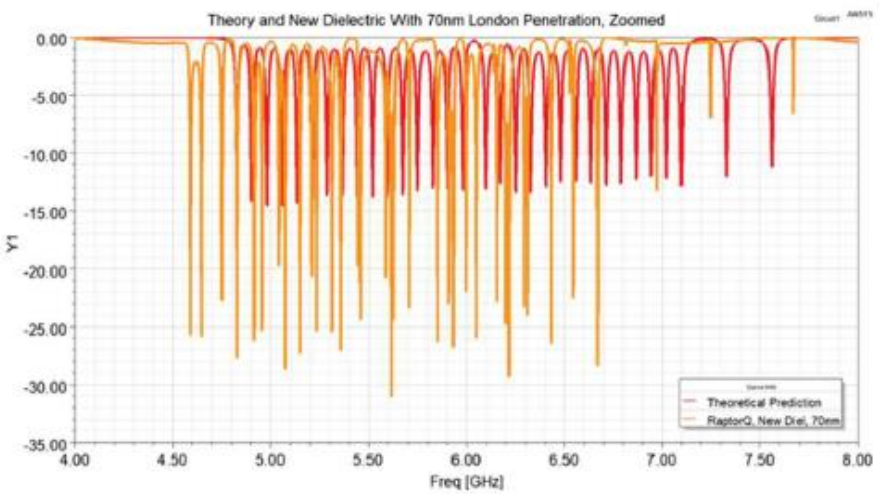

Figure 2: Capturing non-ideal circuit performance for a 32-qubit circuit.

An example of the value, of the RaptorQu technology is illustrated in Fig.2. This is a 32-qubit processor design that captures a total area of 10mm2. RaptorQu enabled the modeling of the entire design capturing all cross-talk and unwanted couplings (orange plot) as opposed to the ideal model of 32 cascaded and uncoupled resonators (red), previously used by the customer.