Improving Photon Number Resolution in Superconducting Nanowire Single-Photon Detectors with Integrated Impedance Tapers

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Introduction

Single photon detectors provide timing information about a digital event – the detection of single quantum of electromagnetic radiation. From an application perspective, achieving high system detection efficiency at short-wave infrared wavelengths, while maintaining the low timing jitter and high counting rate is what makes this technology attractive. This technology is highly desirable for applications in quantum information science, including linear optical quantum computing [1], quantum key distribution [2, 3], quantum repeaters [4], and interplanetary optical communication. In our project we run simulations to optimize the ability to resolve the number of photons detected from the pulse height by a Superconducting Nanowire Single-Photon Detector (SNSPD). It is set up in a manner that features an impedance-matching transmission line taper that provides a characteristic impedance which transitions from 1 kΩ to 50 Ω, with the taper providing an effective load impedance that outputs pulses with not only larger amplitudes but also showed a distinct separation for multi-photon events. The first part of this project tries to computationally match the experimental results obtained by our collaborators at MIT. Once these results are achieved, we try to modify the device geometry to improve the key detector metrics which include timing jitter, dark count rate, reset time, and overall detection efficiency.

Simulation Method

In our simulation, using the AWR Design Environment software, the device is initially broken down into four separate electromagnetic (EM) structures and simulated, then we combined the components into a single circuit schematic – the nanowire meander and three parts of the transmission line taper (see Figure 1 for the combined device), for the purpose of the simulation running faster. The circuit schematic is tested by running two separate simulations. The "Taper" test and the "Pulse" test. The Taper test is designed to look at the frequency-dependent transmission through the taper and it represents how efficiently we can use the taper to couple from the 1 kΩ load impedance to 50 Ω readout impedance. The Pulse test is designed to look at the voltage pulses from the nanowire in a time-dependent simulation. We used four internal ports in the nanowire EM structure to simulate resistive hotspots that represent incident photons absorbed by the nanowire. This allows us to look at how the amplitude of the resulting voltage pulse depends on the number of resistive hotspots. The hotspot resistance is setup as a common variable R throughout the nanowire to show the difference between one-photon and two-photon pulses.

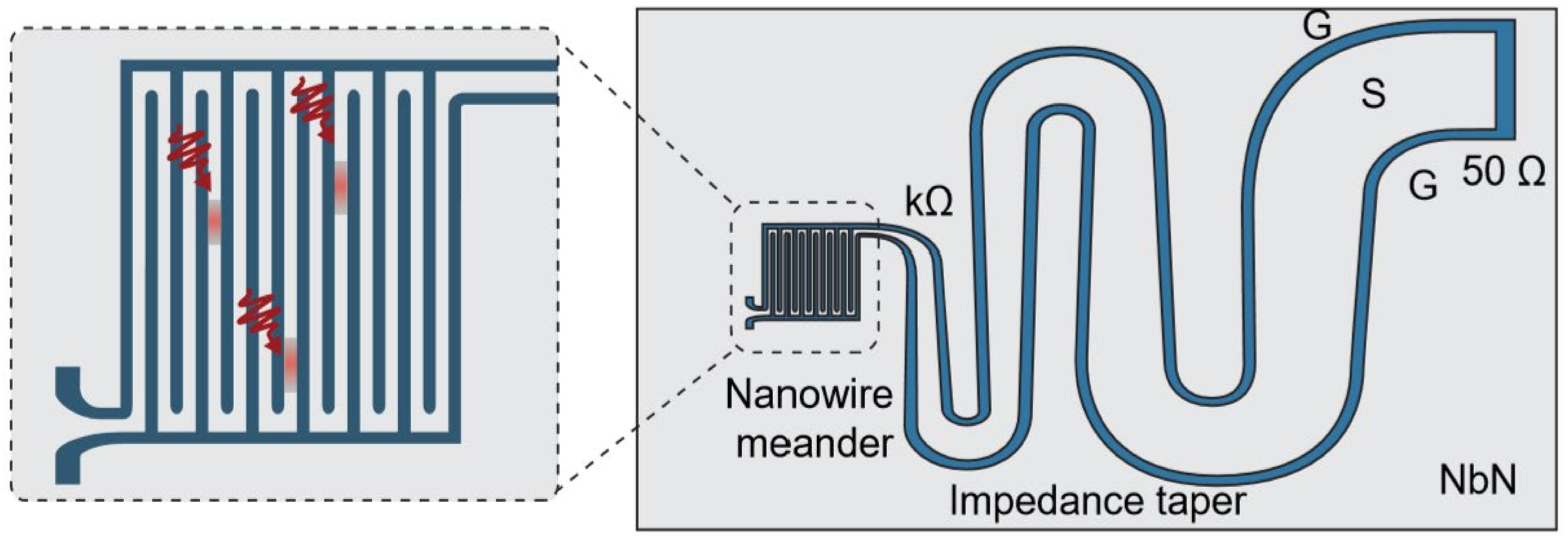

Fig. 1. Shows the nanowire meander and transmission line impedance taper with the zoomed in panel illustrating hotspots created by absorbed photons.

Preliminary Results

The simulations performed show very promising results, Figure 2, our Taper test, the transmission line taper did a good job at matching 1 kΩ to 50 Ω impedance at frequencies above 0.3 GHz. The efficiency of the taper is determined by taking $10 \cdot \log\left(\frac{P_2}{P_1}\right)$, where P_1 is the power going into the 1 kΩ port and P_2 is the power coming out of the 50 Ω port. This logarithmic scale measured in decibels (dB), is known as the transmission coefficient and describes the power ratio of a range of signals. So 0 dB would mean 100% transmission, where $P_2 = P_1$.

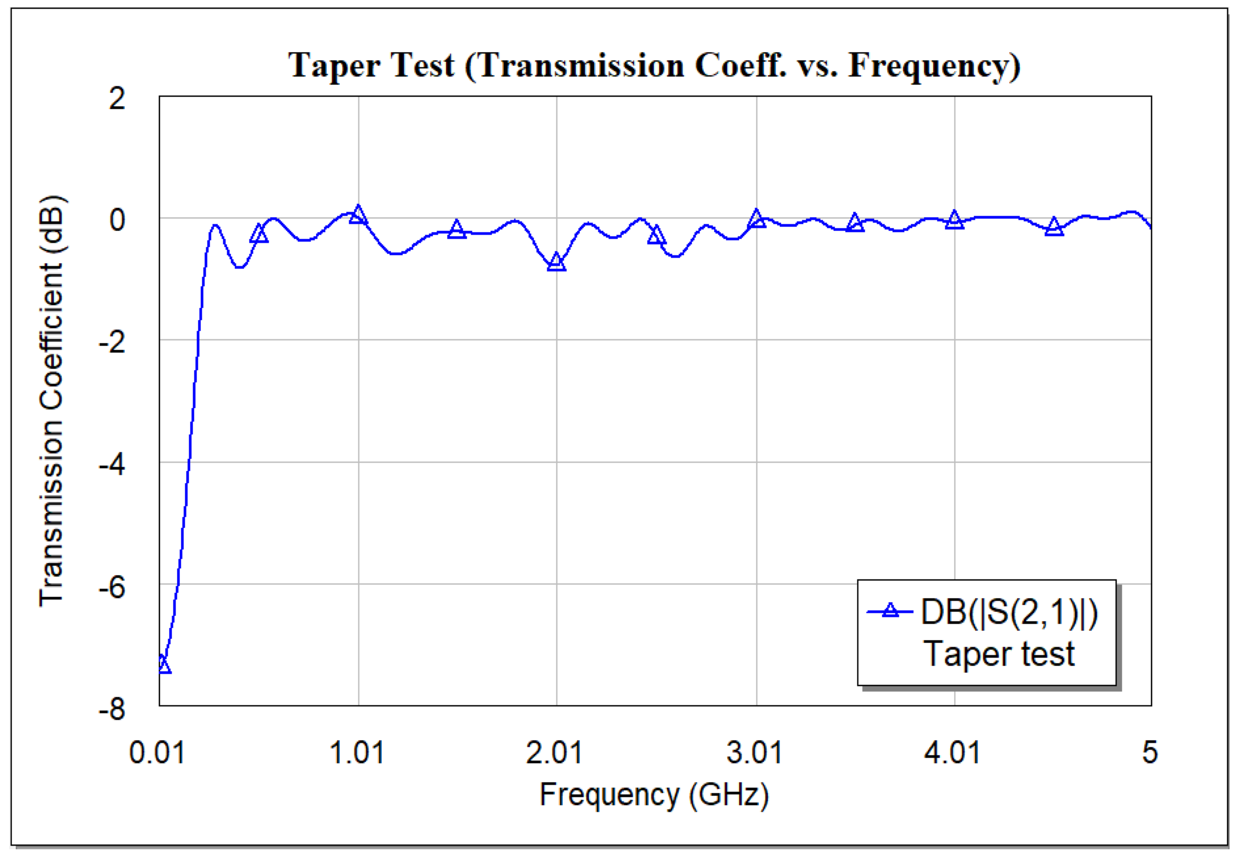

Fig. 2. The graph shows that at frequencies above 0.3 GHz there is a gradual improvement in the efficiency of the taper.

In Figure 3, our Pulse test, is represented by three lines that correspond to three different ports. Port 2 (the blue line) simulates the detection of one photon using a nanowire with no taper. This is the behavior of a typical SNSPD detection pulse. Port 1 (the pink line) is the nanowire with the taper with one resistive region. The rise in the pulse is due to the time delay caused by the added time it takes the pulse to travel the length of the length of the taper. Finally, Port 3 is the same as Port 1 with the exception that this port simulates the simultaneous detection of two photons at different locations and therefore has two resistive regions. We are focused on how the height of the initial post varies with the photon number.

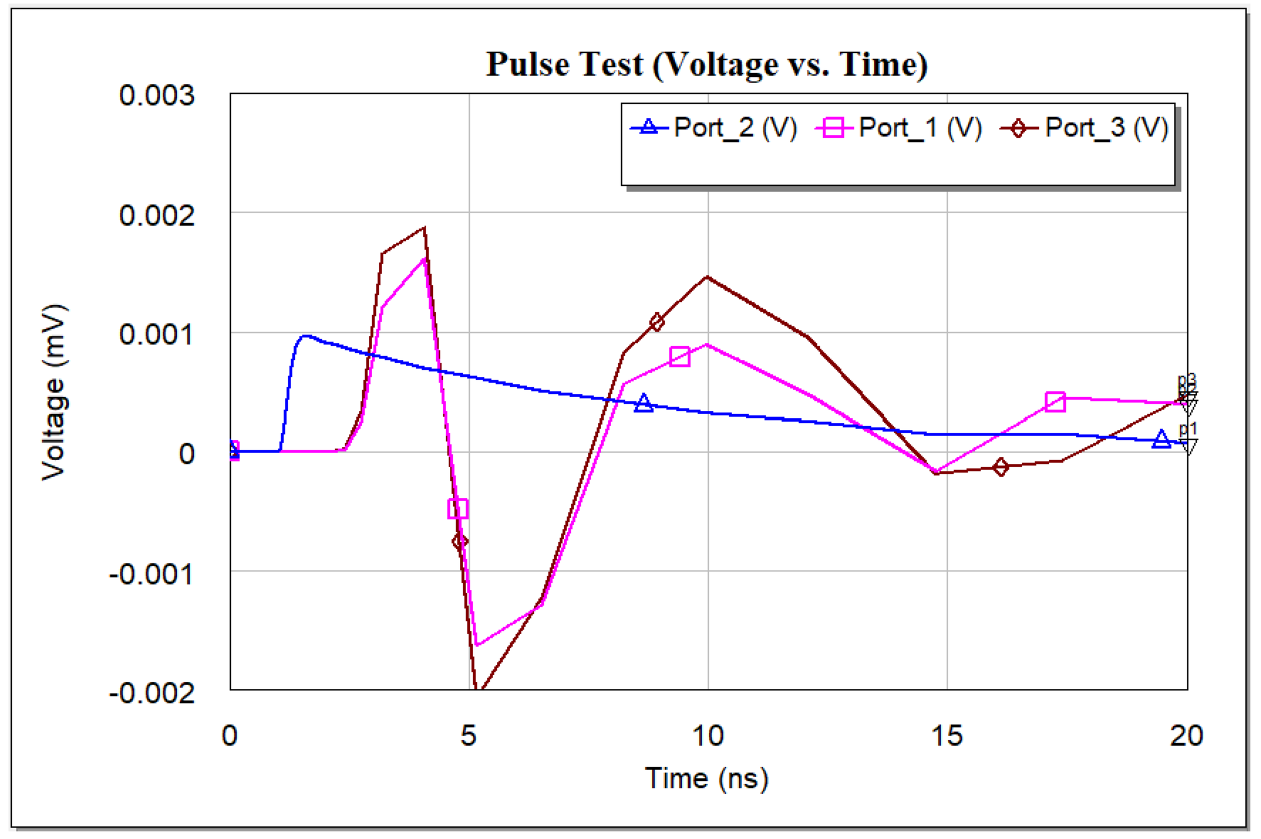

Fig. 3. Simulated pulses at each internal port from the resistive regions made by incident photons on the nanowire.

Conclusion and Future Work

Going forward, we want to make changes to the resistance by varying the photon induced resistive region and seeing how it changes the pulse heights. Additionally, we want to adjust the taper length to a higher impedance to give us a better ability to resolve different numbers of resistive regions, all to try to get the biggest change in amplitude for different numbers of hotspots (representing different numbers of detected photons).

References

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