Superconducting Electronics for the ICF Environment

Martin Wegman

Advisor: Dr. William Donaldson

Abstract

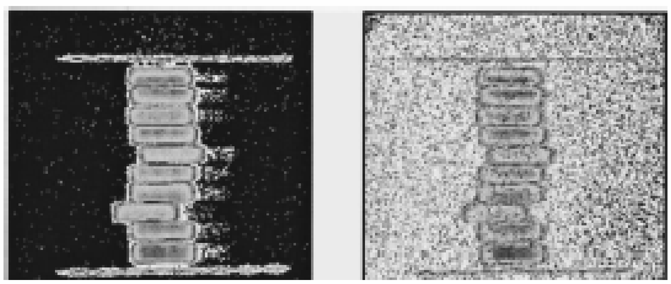
This project addresses the steps necessary to validate the performance of superconducting circuits in an ICF environment. Output signals from diagnostics are often acquired with an oscilloscope. For collecting data on OMEGA a computer program was created to design a circuit board for coupling high-frequency signals into a 5-mm-square Nb superconducting device. Then a superconducting frequency-dividing chip, obtained from HYPRES Inc., was attached to the board with wire bonds. The device was inserted into a cryostat and cooled to 4.2 K. The correct electrical biasing for stable chip operation was determined. A computer program was designed to facilitate communication between the OMEGA Intercommunication Protocol (OIP) Server, Labview, the hardware timing system (HTS) and the Tektronics oscilloscope. All of these pieces were integrated to do on-shot acquisition. Further research will involve testing the level of irradiation hardness of the circuit in the OMEGA Target Bay.

I. Introduction

In inertial confinement fusion (ICF), deuterium and tritium nuclei fuse to produce helium nuclei and energetic neutrons. The OMEGA laser is capable of producing up to

10^{14} neutrons in 250 ps on a single shot.[1] Each neutron has a kinetic energy of 14.1 MeV. Even though they are weakly interacting, at these levels the irradiation from these neutrons can cause severe background noise or damage in semiconducting devices.[2-3]

It is difficult to shield electronic circuits from these neutrons; a concrete wall several feet thick is needed to reduce the flux by about a factor of 1000. Other standard solutions have failed to alleviate the problem. Shielding with hydrogen-rich material leads to spatial and weight concerns. Also, the alternative acquisition medium, conventional film results in a slow cycle time and a poor signal to noise ratio. Hardened semiconductors are expensive and in addition are prone to data loss. The result is that high-yield shots on OMEGA and other ICF systems may either require the devices to be turned off or the collected data may be severely compromised (see Figure 1).



a **b**

Figure 1- Images from a CCD camera located in the OMEGA Target Chamber; (a) a low yield shot, (b) a high yield shot[1]

A promising solution is to employ superconducting circuits, which are naturally radiation hard. Radiation-generated, free electrons become additional carriers in superconducting circuits, but, in contrast to semiconductors, do not add to the conductivity. The question remains how neutrons will affect Cooper pairs.

A Cooper pair has a very fast recovery (18 ps) should a neutron break it apart. If the neutron were to deposit its energy into the superconducting material then there would be a possibility that the material may become non-superconducting.

This project addresses the steps necessary to validate the performance of superconducting circuits in an ICF environment. This project is the first known test of a Niobium superconducting circuit in an environment with a onetime, instantaneous flux of neutrons exceeding 10^{10} within 250ps.

II. Experiment

A superconducting frequency dividing chip was obtained from HYPRES Inc.[4] The chip divides the input frequency by 2^{13}. The circuit is made of Nb with Mo Josephson junctions and a SiO_2 insulator. The pads are Ag with Ti and Pt beneath in a silicon substrate. The chip was measured to be 5,070 microns square. There are two rows of pads on all four sides. The inner square is made of 5 pads and functions as the ground while the outer row of 6 pads functions as input/output and bias lines. The ground pads are separated by 200 microns each while the outside pads are separated by 275 microns each (see Figure 2). There are two identically functioning sides to the chip.

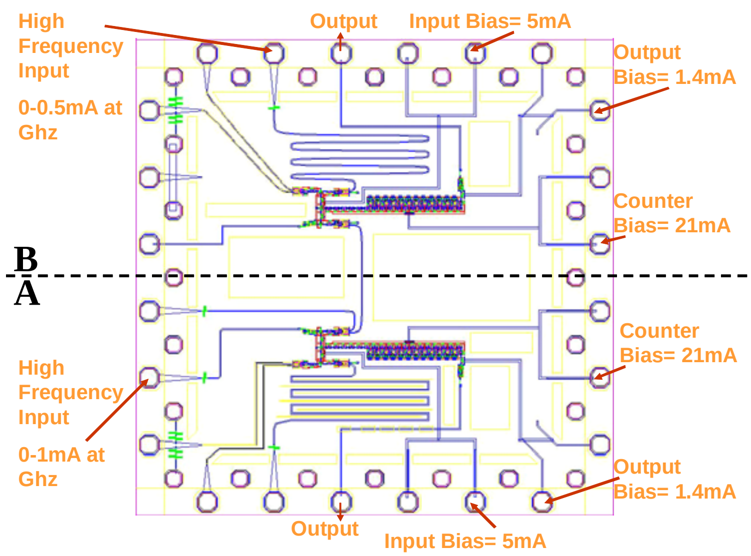


Figure 2- A diagram of the Nb circuit to be tested.

A circuit board with coplanar waveguides was designed to match the 50 ohm impedance of high frequency data acquisition systems and to couple high frequency signals. A coplanar waveguide has a middle, signal-carrying conductor surrounded by two ground strips. The thicknesses of the board and of the strips were 0.06 inches and 0.001 inches, respectively. A PV wave program was created to calculate the impedance using three variables: the size of the middle strip, the size of the two side strips, and the distance separating the strips. The program finds the best size (closest impedance to 50

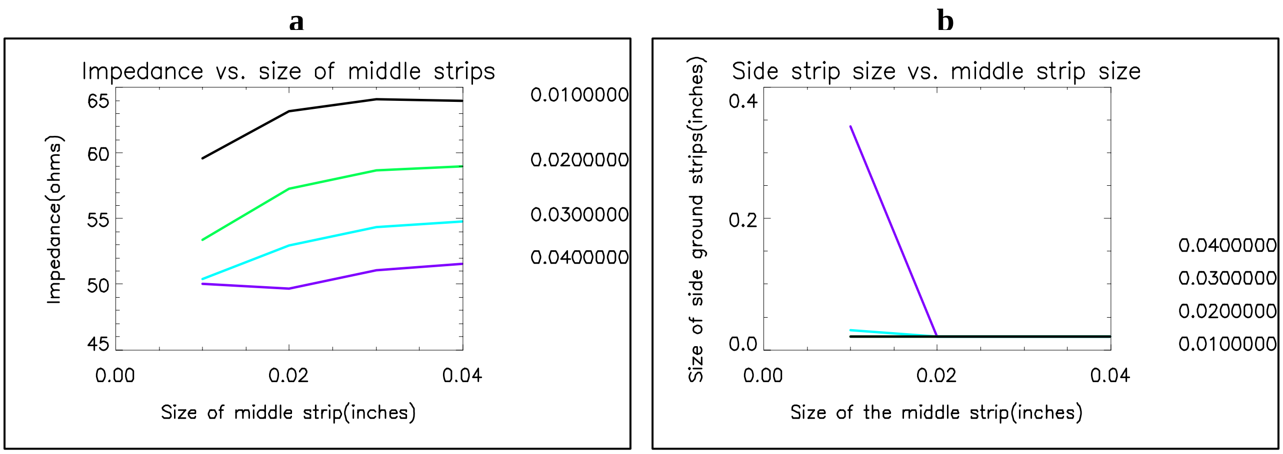


Figure 3- The impedance of the waveguide is a function of the geometry. The impedance will increase with the width of the line (a). The width of the outside lines decreased as the center line increased (b).

ohms) for the side (ground) wires based on the given gap and the size of middle wire. The data is displayed in the two plots of Figure 3. In Figure 3a, the impedance is plotted as a function of the width of the middle wire for four different gap sizes. In Figure 3b, the width of the side ground strips is plotted as a function of the width of the middle wire with impedances as shown in Figure 3a for the four different gap sizes. From Figure 3, the widths of the high and medium frequency strips were determined. The size of the middle (ground) strip was 0.02 or 0.03 inches when the size of the side frequency strips was 0.05 and 0.03 inches respectively, with a gap of 0.05 inches. With a gap of 0.06 inches, the size of the middle strip could be expanded to 0.04 inches with side strips of

0.05 inches. The ground lines and bias lines were made to be 0.03 inches wide each. Using IsoPro, a circuit board was mapped and milled (see Figure 4).

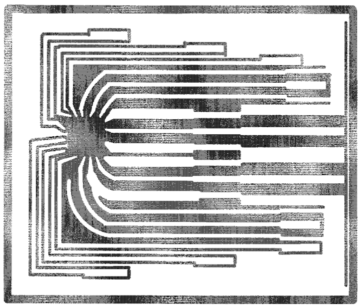


Figure 4- Circuit board design for connecting the Nb superconducting chip.

Using a West Bond wire-bonder, bonds were made with Al wire between the respective leads and pads. The machine used was located in the Advanced Integrated Circuits Laboratory in the Computer Science Building at the University of Rochester. The settings for bonding to the copper board were Power: 2.9 grams and Time: 4.5 ms and the setting for the Au pad was Power: 3.7 grams and Time: 4.1 ms.

The correct electrical biasing for stable chip operation was determined. To achieve an input bias of 5 mA, a 9V power source was placed in series with an 1800 ohm resistor. For the correct output bias with 1.4 mA, a different 9V power source was placed in series with a 430 ohm resistor. Finally, for a 21mA counter bias, a 9V source was placed in series with a 6,000 ohm resistor. The input wave from a Coherent 7600 Mode Locker 38 MHz frequency generator was modified (25 mV offset) using a bias tee with a DC power supply to produce an Rf input with a bias of 0 – 1 mA (side A). A series of attenuators 20dB, 10dB, 8dB, 6dB and 3dB were used in series to reduce the voltage of the 38 MHz signal.

To determine the correct output setup, the output was run first through a frequency filter and then through a quad amplifier into a Tektronics TDS 6604 fast oscilloscope. The OMEGA hardware timing system was then attached to the oscilloscope. A laptop was attached to the oscilloscope via a GPIB connection.

A Labview/ Visual Basic computer program was designed to communicate with the OMEGA Intercommunication Protocol (OIP) Server, Labview, the hardware timing system (HTS) and the Tektronics oscilloscope. Calling a previously written Visual Basic program which waits for events from the OIP Server, the Labview program can trigger and acquire waveform data from the oscilloscope and store the data on the PC during the OMEGA shot. The program can handle all OMEGA events and has a WatchDog timer. It was tested using the OIP imitation program and with the actual OIP server.

All of these pieces were integrated to do on-shot acquisition. The circuit board was mounted in a brass, cylindrical cryostat one foot in diameter and approximately 3 feet tall. The bottom can be removed for mounting the board and connecting the bias, input and output lines. A conductive grease was spread beneath the board and all wires attaching to the board were heat sunk or attached to the inside of the cryostat before being attached to the board.

A vacuum reduces the pressure inside the cryostat to 20 mTorr. Then the outer chamber is cooled to ~70 K with liquid nitrogen. A half cup full of nitrogen is added to the inner chamber to help clear out water vapor. After this boils, liquid helium is added so that the circuit is at its superconducting temperature, 4.2 K.

Precautions were taken to shield all exposed wires from EMI with reflective aluminum wire wrap. Several ground wires were run from the cryostat itself.

The experimental setup includes placing the cryostat in the Target Bay on a pedestal (~one meter above the floor) in the direct line (not behind other sensory equipment) of the target chamber center (TCC). The laptop and scope will be placed in La Cave, below the Target Bay.

III. Analysis

Several issues are involved in planning the experimental setup. First and very important, data acquisition must occur on shot. Second, correct trigger timing must occur for the oscilloscope with the HTS. Finally, there can be no disruption of the principal OMEGA experiments.

The goal is to analyze the period of the counter output recorded during the neutron flux (OMEGA firing). The 38 MHz frequency should be divided by 2^{13} to produce an output of ~4638 Hz. This converts to an output with a peak every 216 us. The acquired waveform will be in the 4000 us range, enough to capture 16 full periods and analyze the output's wavelengths during the shot. If a neutron were to interrupt the circuit, the period would decrease thereby resulting in a higher frequency than expected.

Several control tests will validate the above results. First, a bit error rate (BER) test will be performed. This involves testing the circuit in a non-neutron/low-neutron environment to determine random error. The circuit will be placed 180 cm from TCC or in La Cave. It will be given a test pattern to read during OMEGA firing. Analyzing the data, the number of misread bits will characterize the probability of error. After the high neutron yield shot another BER test will be performed to assess whether any permanent damage occurs from neutron degradation. This cycle will then be repeated several times.

Theoretical calculations were performed to assess the viability of superconducting circuits. In one calculation, it was determined that to raise the temperature (from 4.3 K) of all the Nb (3.23E-10 g) in the circuit to its non-superconducting temperature (9.2 K) would require 200 (18 MeV) neutrons. So for a circuit temperature to be raised equal to T_c a yield of 1.68E+10 neutrons from a DT shot is required when the device is located 10 cm from TCC. At 280 cm from TCC (experimental location on the pedestal), 3.30E+14 neutrons from a DT reaction would raise the temperature to 9.2 K. In La Cave, a yield of 1.42E+15 neutrons should result in the same disruption. Note that the preceding calculations were based on the assumption that the neutrons' quantum efficiencies of the energy deposition are 100%, which is unlikely. So, it is unlikely that the superconducting circuit will be disrupted.

These calculations are based on the assumption that the whole circuit has to be heated, when, in fact, only a single segment of the RSFC circuit needs to be made non superconducting to allow for disruption in the quantized flux stored.

IV. Conclusion

Data obtained using semiconductors and their alternatives have been compromised in high neutron-yield environments.

In this project, an experimental setup was designed to test the viability of superconducting circuits. A circuit board was created, and the correct electrical bias was determined. A computer program was designed to facilitate communication between the OMEGA Server, a fast oscilloscope and the hardware timing system. Additionally, theoretical calculations give evidence of the circuit's viability.

Further tests on OMEGA will hopefully support these findings.

V. References

[1] P.A. Jaanimagi, R. Boni, and R. L. Keck, "Neutron-induced background in charge-coupled device dectors", Review of Scientific Instruments, Vol. 72, No. 1, (2001).

[2] N. Rando, A. Poelaert, R. den Hartog, D. Lumb, P. Verhoeve, A. Peacock, B. Nickson, L. Adams, W. Hajdas, "Proton induced radiation damage on high quality Superconducting Tunnel Junction Detectors", Nuclear Instruments And Methods A 394 (1997) 173-179.

[3] S. E. King, R. Magno, and W. G. Maisch, "Radiation Damage Assessment Of Nb Tunnel Junction Devices", IEEE Transactions on Nuclear Science, Vol. 38, No. 6, (1991).

[4] S. Sarwan, D. Gupta, A. F. Kirichenko, T. Oku, C. Otani, H. Sato, and H. Shimizu, "High-sensitivity high-resolution dual-function signal and time digitizer", Applied Physics Letters, Vol. 80, No. 11, (2002).

VI. Acknowledgments

I would like to thank the following members of the LLE community for their help: K. Ebbecke and A. Elias, Electronics Shop; A. Pearlman and J. R. Park, graduate students; and L. O'Heron. A special thanks to Dr. R. S. Craxton for selecting me for the summer program and to my advisor Dr. W. Donaldson.