High-Frequency Crossbar in Superconducting Microstrip Waveguide Interconnects

I. Introduction

Superconducting electronic circuits offer a range of important advantages over their normal conducting counterparts for many applications, such as cryogenic or miniaturized electronics. These advantages include reduced power consumption, increased bandwidth, and faster switching speeds. The use of superconductors in these circuits is facilitated by the availability of materials that exhibit superconductivity at temperatures above 4 K. These materials, such as niobium and aluminum, are suitable for use in superconducting electronic devices because they maintain their superconducting properties at temperatures above 4 K.

II. Experiment

The experiment described in this section demonstrates the operation of a superconducting electronic circuit. The circuit is designed to perform a simple logic function, such as an AND gate, and is fabricated using superconducting materials. The circuit is tested by applying a series of input signals and measuring the output signals. The results of this test are used to verify the functionality of the circuit.

Conclusion

The demonstration of the circuit in this section demonstrates the potential of superconducting electronic circuits for a range of applications. The use of superconducting materials in these circuits offers a number of advantages, including reduced power consumption, increased bandwidth, and faster switching speeds. These advantages make superconducting electronic circuits ideal for use in applications where these advantages are critical.

References


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Abstract: This work presents a superconducting electronic circuit that performs a logic function. The circuit is fabricated using superconducting materials and tested for functionality. The results of this test are used to demonstrate the potential of superconducting electronic circuits for a range of applications.
attenuation, and dispersion, special long superconducting Nb waveguide circuits were fabricated [5], as shown in Fig. 1. A 30-μm x 30-μm Nb MSM photodiode with a finger width and spacing of 1 μm was coupled onto a long, 14.25-μm-wide microstrip waveguide, with 0.85 μm of SiO₂ between the ground plane and the top conductor. The MSM diodes generated electrical pulses with a rise time of <3 ps and a full width at half-maximum (FWHM) of 5.0 ps at 2.15 K. These pulses traveled along the 8280-μm length of Nb microstrip waveguide that was fabricated in a meander structure to allow nodal probing of the propagating pulse. The signal was measured at 100 μm, 575 μm, 1050 μm, 2100 μm, and 5060 μm from the MSM diode, as shown in Fig. 1. Fig. 2 shows data sampled at two of these nodes: 575 μm and 5060 μm. The two pulses measured nearly 4500 μm apart appear identical, indicating a minimal amount of attenuation and dispersion from the microstrip. At all sampling points the pulse appeared to have suffered no attenuation or dispersion at a temperature of 2.15 K, as can be seen in Fig. 2.

![Sampling nodes Nb microstrip transmission line](image)

Fig. 1. Meander design for nodal measurements of pulse propagation on a Nb microstrip waveguide with our EO sampling system. Superimposed on the picture are the nodes at which the sampling/laser beam was positioned.

Since the microstrip transmission line is terminated with a large pad, i.e. a much lower impedance, the reflection of the pulse from the end of the transmission line looks like that from a nearly ideal short circuit. When compared with the original pulse, the reflection from the end of the microstrip waveguide appears identical to that of the original pulse. This represents lossless transmission over a total propagation distance of ~11.5 mm. Additional data were collected over a 2- to 10-K temperature range to examine the waveguide propagation characteristics above, below, and near the superconducting transition of Nb. From this data, we have calculated the group velocity, attenuation, and dispersion of the propagating broadband signal, thereby characterizing the microstrip line. These results are discussed in section III.

C. Crosstalk Between Niobium Microstrip Waveguides

The microstrip waveguides described above are used for interconnects in SFQ circuits. These interconnects are implemented on several metallization layers and often cross above and below one another. The broadband nature of the propagating pulses on these waveguides increases the possibility of crosstalk between waveguides at each of these crossings. We examined the crosstalk between microstrip waveguides by fabricating two microstrip lines perpendicular to each other on two different metallization layers, as shown in Fig. 3. The lower (M2) layer was 6.5 μm wide and separated from the ground plane by 0.35 μm of SiO₂. The upper (M3) layer was 14.25 μm wide with a 0.85-μm SiO₂ spacing from the ground plane. The overlap area between the two waveguides was 6.5 μm x 14.25 μm, separated by a 0.5-μm-thick layer of SiO₂. Two 30-μm x 30-μm Nb MSM photodiodes (one on each microstrip line) were used to produce the broadband electrical pulses. Using the EO sampling system, a pulse was generated on one of the transmission lines and then measured on both that line and the microstrip line that crosses it, as shown in Fig. 3. Fig. 4 shows the transient measured on the signal line, in which the MSM diode produced 180-mV pulses with a 2.7-ps rise time. This input pulse was then coupled onto the crossing microstrip waveguide, generating the crosstalk signal also shown in Fig. 4. The measured crosstalk signal appears as a single-cycle oscillation with an amplitude of approximately 2 mV. By comparing these signal and crosstalk measurements, the coupling characteristics of the interconnects are determined.

III. DISCUSSION

A. Niobium Microstrip Waveguides

The group velocity of the pulses was measured by dividing the distance traveled on the microstrip by the corresponding time delay of the pulse. The pulse arrival time
was determined by the time at which the pulse was at 50% of its peak value. This is a common practice since pulses may disperse, causing their peaks to convey an inaccurate arrival time. In our particular case, however, the results from either method agree due to the lack of pulse dispersion. The measured group velocity of a 14.25-μm-wide Nb microstrip transmission line with a 0.85-μm SiO₂ insulating layer at 2.15 K is 121.4±0.5 μm/ps. The resulting value is in agreement from several tests; both the nodal analysis method and the observation of the pulses reflected from the termination pad. In fact, the reflected pulses give the most precise values since the propagation distance is the longest.

As the temperature was increased to ~7 K, the pulses began to be attenuated when traveling distances >1 cm and the group velocity decreased slightly, by ~1 μm/ps. By 8.5 K, the reflected pulse from the end of the transmission line was heavily attenuated, and the propagating pulse 1060 μm from the MSM diode was dispersed with the rise time increasing by ~0.5 ps and the FWHM increasing by ~1 ps. The group velocity dropped by ~8%. At 9.2 K, just below the critical temperature for Nb, the pulse at 1060 μm from the MSM diode was broadened to ~15-ps FWHM with a rise time of ~7 ps and the reflected pulse was no longer observable. Increasing the temperature above T_c to 9.9 K, the measured pulse at 1060 μm from the MSM diode was broadened to 33 ps, severely attenuated, and contained no measurable reflection.

The results of these experiments are encouraging for our nodal characterization of superconducting circuits. The short pulses and nodal probing create a broadband, time domain tool for examining circuits. The measured group velocity agrees quite well with calculations based on line capacitance and impedance. The inductance was calculated using the FastHenry-2.0S program written by Stephen Whiteley [6], and the capacitance was calculated using a simple parallel-plate capacitor model. The relative dielectric constant used for the SiO₂ layer was 5.45 [5], a value higher than bulk SiO₂, indicating oxygen depletion during the sputter deposition and possibly a contribution from the NbO₃ formed at the interface. Using the above data, the calculated value of the group velocity—124.6 μm/ps—agreed very well with the measured value of 121.4±0.5 μm/ps.

The data for the attenuation and dispersion of the Nb line are also quite extraordinary. The time domain data was converted to frequency domain by Fourier transform. The broadband nature of these pulses having a 3-dB bandwidth of 95 GHz is shown in Fig. 5. Here the attenuation and dispersion were examined in a more quantitative fashion. The results of this study show no observable dispersion in the pulses at 2.15 K, for frequencies beyond 100 GHz and lengths of 1 cm.

### B. Crosstalk Between Niobium Microstrip Waveguides

The crosstalk was measured on lines fabricated on the M2 and M3 metallization layers, separated by a 0.5-μm-thick SiO₂ layer. These structural dimensions as well as the bipolar crosstalk signal suggest that the coupling mechanism is capacitive. To test this idea, a simple capacitive coupling simulation was performed. The capacitance between the lines

![Crosstalk between two Nb microstrip lines crossing perpendicular to each other and separated by a 0.5-μm SiO₂ insulating layer. The response of the MSM diode (dashed) was measured to have a rise time of 2.1 ps with a FWHM of 5.3 ps at 2.15 K.](image)

**Fig. 4.** Crosstalk between two Nb microstrip lines crossing perpendicular to each other and separated by a 0.5-μm SiO₂ insulating layer. The response of the MSM diode (dashed) was measured to have a rise time of 2.1 ps with a FWHM of 5.3 ps at 2.15 K.

![Magnitude vs. Frequency](image)

**Fig. 5.** The Fourier transform of the pulse measured at different locations shows the broadband nature of the MSM diode and the Nb microstrip transmission line. The 3-dB bandwidth is 95 GHz.

![Sampling points](image)

**Fig. 3.** EO sampling experiment measuring a picosecond pulse on a microstrip waveguide and this pulse’s crosstalk on a crossing microstrip waveguide. Sampling beam positions are sketched on top of the picture.
was modeled as a simple parallel-plate capacitor of area 6.5 \( \mu \text{m} \times 1425 \mu \text{m} \) separated by distance of 0.5 \( \mu \text{m} \). This gives a coupling capacitor value of 6.4 \( \text{fF} \) assuming the standard dielectric value of SiO\(_2\), \( \varepsilon_r = 3.9 \). Using digitized data from the MSM diode as an input, the crosstalk signal was simulated. The shape of the response matched, but the amplitudes were different. Due to the sputtering of the insulating layer between the waveguides, as discussed in section III A., we know that the real dielectric value is actually higher than that of bulk SiO\(_2\); thus, the crosstalk data allows us to independently confirm the value of the dielectric. Fig. 6 shows a good agreement fit between the simulation and the measured data. The fit provides a capacitance of 7±2 \( \text{fF} \), establishing a relative dielectric value of \( \varepsilon_r = 4.3 \pm 1.2 \).

The experimentally measured signal is also offset in time by 1.8 ps from the simulated value. This separation in time exactly matches the extra time incurred by the crosstalk signal as it propagated along the additional length of microstrip line, as can been seen in the device layout in Fig. 3. A reflection of the crosstalk signal from the end of the waveguide also matches perfectly with the established propagation velocity. This additional evidence reinforces the effectiveness of our capacitive coupling model.

With these experimental values established we now consider the implications of this crosstalk signal as it pertains to undesirable circuit noise. Current superconducting digital electronics circuits operating with SFQ logic use Josephson junctions with a McCumber parameter of about 2 and have critical currents of around 250 \( \mu \text{A} \). For these circuits, a SFQ pulse has a peak voltage of 0.7 mV and a 3-dB bandwidth of 200 GHz. A SFQ pulse like this would produce a crosstalk signal with a positive peak value of 12 \( \mu \text{V} \) and negative peak of -18 \( \mu \text{V} \). By comparison, the Johnson noise from a resistive source of 2 \( \Omega \) at 4.2 K with a bandwidth of 200 GHz is 9.6 \( \mu \text{V} \). This indicates that the crosstalk may overtake the circuit noise as the dominant source of error in SFQ circuits. Further, the crosstalk noise considered above includes only a single crossing, while actual LSI circuits can have much higher values due to multiple crossings of waveguide interconnects. Finally, current SFQ circuit designs fabricated at HYPRES utilize the M1 and M2 metal layers. These layers are 2.5 times closer to one another, thereby increasing the crosstalk signal by this amount. To reduce this crosstalk noise, circuit designers should implement narrower waveguide dimensions combined with more stringent design rules.

IV. CONCLUSION

Niobium superconducting microstrip waveguides provide lossless data transmission over 1-cm distances for signals with frequencies up to 100 GHz. The group velocity on these structures was measured to be 121.4±0.5 \( \mu \text{m}/\text{ps} \). When used as high-speed interconnects in SFQ logic circuits, the crossing of these waveguides results in undesirable crosstalk signals that increase the circuit noise. For small overlap areas in the SFQ circuits, the crosstalk is well described by a simple capacitive coupling model. The results compare favorably with those from calculations and provide feedback for optimization of circuit margins. The experiments also demonstrate the ability of our EO sampling system to perform in-situ, nodal testing on superconducting structures, providing a powerful tool for ultrafast characterization of superconducting circuits.

REFERENCES