PERGAMON

PICOSECOND NODAL TESTING OF CENTIMETER-SIZE SUPERCONDUCTING Nb MICROSTRIP INTERCONNECTS

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Abstract—We have implemented a low-temperature electro-optic sampling system for non-invasive, nodal testing of superconducting Nb integrated circuits. With submillivolt sensitivity and a subpicosecond temporal response, this system has been used to perform nodal analysis on rapid-single-flux quantum (RSFQ) devices and superconducting microstrip interconnects. Here we demonstrate that by measuring the propagation of 6-ps-wide pulses at various test nodes, we are able to fully characterize a superconducting microstrip waveguide the size of an entire chip. The transmission line was selected not only to perform the first complete characterization of a superconducting microstrip, but also to demonstrate full nodal testing of a foundry-fabricated RSFQ integrated circuit. Finally, our results provided much-needed feedback for improving computer simulations of superconducting digital circuits. © 1999 Elsevier Science Ltd. All rights reserved

INTRODUCTION

We have implemented a cryogenic electro-optic (EO) sampling system to characterize RSFQ [1] superconducting electronic devices [2, 3]. This sampling system is capable of measuring ultrafast electrical transients with a temporal resolution of < 200 fs and a voltage sensitivity of < 100 μ V. The heart of the EO sampling system is a Ti:sapphire laser capable of generating 2-W, 60-fs pulses at 800 nm with a repetition rate of 76 MHz. This laser is used to excite and probe the tested devices. A beamsplitter generates two beams from the output of the laser: a switching beam and a sampling beam.

The switching beam is frequency doubled and steered through an optical window into a cryostat and onto an optoelectronic (OE) switch to provide the input to our device under test (DUT). The cryostat is capable of operating between 2 K and 300 K. The OE switches used in these experiments are Nb metal-semiconductor-metal (MSM) photodiodes. MSM diodes are capable of producing short pulses on a variety of semiconducting substrates due to the quasi-ballistic motion of photogenerated carriers across micrometer-size gaps. In addition, MSM diodes appear as open-circuit elements in their off state and therefore do not interfere with the operation of the DUT [4].

The sampling beam is sent to a retroreflector mounted on a mechanical translation stage to provide an adjustable time delay between the switching and sampling beams. The sampling beam is then focused through a microscope objective onto an EO crystal (LiTaO_3) which sits on top of the DUT. The sampling beam can be focused as small as 2 μm , which primarily defines the system's spatial resolution. A fringing electric field from the sample which passes into the LiTaO_3 crystal differentially alters the refractive index. The differential change in refractive index is impressed upon the sampling beam, which is then detected with photodetectors and conventional electronics [3].

Not only does the EO sampling system offer orders of magnitude improvement in voltage and temporal resolution over conventional sampling oscilloscopes, it also offers a non-contact probe which can be moved anywhere on a DUT. This provides a non-invasive, in situ testing scheme for integrated circuits.

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EXPERIMENT

Group velocity, attenuation and dispersion of Nb microstrip transmission lines

An integral part of RSFQ logic is the propagation of SFQ pulses along microstrip transmission line interconnects. However, many basic properties of these transmission lines such as group velocity, attenuation and dispersion have not been directly measured. To examine this, superconducting Nb circuits were fabricated on Si [5]. The OE switch was a $30 \times 30 \mu\text{m}$, Nb MSM photodiode with a finger width and spacing of $1 \mu\text{m}$. The MSM diode was coupled onto a long microstrip transmission line, $14.25 \mu\text{m}$ wide and with $0.85 \mu\text{m}$ of SiO_2 between the ground plane and the top conductor. The microstrip transmission line was fabricated in a meander structure to allow nodal probing at 50, 500, 1000, 2000, and $5000 \mu\text{m}$. By sampling at these nodes, we have measured the group velocity, attenuation and dispersion of the propagating broadband signal, thereby characterizing the microstrip line. The data were collected over a temperature range of 2–10 K to examine the characteristics above, below and near the superconducting transition of Nb.

Crosstalk of Nb microstrip transmission lines

At densities of RSFQ circuits, interconnects are implemented on several metallization levels. These levels often cross above and below one another, which may lead to crosstalk between circuits. We examined the crosstalk between microstrip transmission lines by fabricating two microstrip lines perpendicular to each other on two different metallization layers. The lower (M2) layer was $6.5\text{-}\mu\text{m}$ wide and separated from the ground plane by $0.35 \mu\text{m}$ of SiO_2 . The upper (M3) layer was $14.25\text{-}\mu\text{m}$ wide with a $0.85 \mu\text{m}$ SiO_2 spacing from the ground plane. The overlap area between the two transmission lines is $6.5 \mu\text{m} \times 14.25 \mu\text{m}$, separated by a SiO_2 layer of thickness $0.5 \mu\text{m}$. Two $30 \mu\text{m} \times 30 \mu\text{m}$, Nb MSM photodiodes (one on each transmission line) were used to produce the broadband electrical pulses. Using the EO sampling system, a pulse was generated on one transmission line, and then measured on both that line and the microstrip line which crosses it. By comparing these two results, the crosstalk between the two lines is determined.

RESULTS

Group velocity, attenuation and dispersion of Nb microstrip transmission lines

The MSM diodes generated electrical pulses with a rise time of ~ 3 ps and a full-width-at-half maximum (FWHM) of < 6 ps at 2.15 K. The pulses traveled along the $8280\text{-}\mu\text{m}$ length of Nb microstrip transmission line and were measured at 100, 575, 1050, 2100, and $5060 \mu\text{m}$ from the MSM diode. At all of the sampling points the pulse appeared to have suffered no attenuation or dispersion, at a temperature of 2.15 K (Fig. 1). 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 transmission line (a total propagation distance of ~ 11.5 mm) appears identical to that of the original pulse.

The group velocity of the pulses was measured by dividing the distance traveled on the microstrip line by the corresponding time delay of the pulse. The pulse arrival time was determined by the time at which the pulse is at 50% of its peak value. This is a common practice since pulses may disperse and therefore their peaks may not accurately convey the arrival time. However, in this case, the results from either method agree due to the lack of dispersion. The measured result of the group velocity of a $14.25\text{-}\mu\text{m}$ -wide Nb microstrip transmission line with a $0.85 \mu\text{m}$ SiO_2 insulating layer at 2.15 K is $121.4 \pm 0.5 \mu\text{m/ps}$. The resulting value is in agreement from several tests: the nodal analysis method as well as values obtained from observing the reflected pulses. In fact, the reflected pulses give the most precise values since the propagation distance is much greater.

As the temperature is increased to ~ 7 K the pulses begin to be attenuated when traveling distances > 15 mm and the group velocity has decreased slightly, by $\sim 1 \mu\text{m/ps}$. By 8.5 K the reflected pulse from the end of the transmission line is heavily attenuated, and the propagating pulse $1060 \mu\text{m}$ from the MSM diode has been dispersed (Fig. 2) with the rise time increasing by

Fig. 1. Electro-optic detection of a pulse propagating on a Nb microstrip transmission line at 2.15 K, measured at 575 μm and 5060 μm from the MSM diode. The FWHM remains the same as the initial pulse, 5 ps. Note: the small shoulder following the pulse is an artifact of the measurement and not a propagating signal.

~ 0.5 ps and the FWHM increasing by ~ 1 ps. The group velocity has dropped by $\sim 10 \mu\text{m}/\text{ps}$. At 9.2 K, just below the critical temperature for Nb, the pulse at 1060 μm from the MSM diode is broadened to ~ 15 ps FWHM with a rise time of ~ 7 ps and the reflected pulse is no longer observable. Increasing the temperature above T_c to 9.9 K, the measured pulse at 1060 μm from the MSM diode is broadened to 33 ps, is severely attenuated, and contains no measurable reflection.

Crosstalk of Nb microstrip transmission lines

The crosstalk was measured on lines fabricated on the M2 and M3 metallization layers, separated by a $0.5 \mu\text{m}$ thick SiO_2 layer. Increasing the light intensity on the MSM diode created a propagating pulse on the signal line (M3) with peak amplitude 185 mV. The sampling beam measured the signal line pulse as well as a pulse with a 3 mV peak amplitude on the crossed (M2) line. The arrival time of this pulse agrees with that of a crosstalk signal. Therefore, the measured crosstalk signal was -36 dB (Fig. 3).

Fig. 2. This pulse was measured at 8.5 K on the Nb microstrip line 1060 μm from the MSM diode. The main pulse is slightly attenuated and broadened, while the negative reflection at ~ 140 ps is noticeably attenuated and dispersed after an additional 14.4 mm of propagation.

Fig. 3. Crosstalk between two Nb microstrip lines crossing perpendicular to each other and separated by a $0.5 \mu\text{m}$ SiO_2 insulating layer. The response of the MSM diode was measured to have a rise time of 2.1 ps with a FWHM of 5.3 ps at 2.15 K.

DISCUSSION

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-2.0 S 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 SiO_2 layer was 5.45 [5], a value higher than bulk SiO_2 , indicating oxygen depletion during the sputter deposition and possibly a contribution from the NbO_x formed at the interface. Using this data, the calculated value of the group velocity $124.6 \mu\text{m}/\text{ps}$ agrees very well with the measured value of $121.4 \pm 0.5 \mu\text{m}/\text{ps}$.

The data for the attenuation and dispersion experiments are also quite extraordinary. The time domain data was converted to frequency domain by Fourier transform, Fig. 4. 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, up to a bandwidth of ~ 100 GHz. Thus, Nb microstrip transmission lines can be modeled as lossless transmission lines for frequencies up to 100 GHz and lengths of up to 1 cm.

The crosstalk coupling between the Nb microstrip lines seems to follow a capacitive coupling model. The capacitance between the lines was modeled as a simple parallel plate capacitor of

Fig. 4. 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.

area $6.5\ \mu\text{m} \times 14.25\ \mu\text{m}$ separated by distance of $0.5\ \mu\text{m}$. This gives a coupling capacitor value of 8.94 fF. The crosstalk calculation gives a coupling of $-31\ \text{dB}$ for a 100 GHz signal. This simple calculation shows good agreement with our measured value of $-36\ \text{dB}$. Thus, we attribute most of the crosstalk to capacitive coupling.

CONCLUSION

Our experimental analysis of Nb superconducting microstrip transmission lines has uncovered their remarkably low attenuation and dispersion for frequencies up to 100 GHz. In addition, we have measured the group velocity and crosstalk of these transmission lines. The results compare favorably with those from calculations, and provide feedback for the Nb circuit designers by confirming the accuracy of their simulations. The experiments have also demonstrated the ability of our cryogenic EO sampling system in performing nodal testing on superconducting structures. This in situ measurement technique is a powerful tool for ultrafast characterization of superconducting circuits.

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