

# Experimental Investigation of a 220 GHz Planar Multiple Bridges Superconducting Switch

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**Abstract**—We present preliminary measured responses of a planar superconducting on/off switch centred at the 220 GHz. The superconducting switch, comprising three niobium nitride (NbN) bridges, deposited across the slotline section of a back-to-back unilateral finline, made of a similar superconducting material. The transmission characteristics of the superconducting switch illuminated by a sub-millimetre source were measured using a superconductor-insulator-superconductor (SIS) chip as direct detector. The NbN bridges were switched from the superconducting state to the normal state by a bias current exceeding the critical current of the bridges. With this arrangement, we have measured a switching dynamic range of  $\sim 13$  dB at 245 GHz, demonstrating the successful operation of the multiple NbN bridges planar superconducting on/off switch.

## I. INTRODUCTION

A planar lossless superconducting switch without any moveable parts that can be used to modulate millimetre and sub-millimetre signal with high switching speed is important for various astronomical experiments operating in this wavelength regime. In particular fast planar switching is essential in constructing ultra-sensitive instruments to measure the polarisation state of the Cosmic Microwave Background (CMB) signals [1], and the bolometric interferometry instruments where the beams are combined at RF frequencies. A planar-circuit switch design would also allow easy integration with the detector circuits.

The planar superconducting switch we consider here comprises three narrow strips fabricated across a slotline fed directly by two back-to-back unilateral finline tapers, as shown in Fig. 1. These bridges were formed using high normal resistance niobium nitride (NbN) film of 50 nm thick. Each NbN bridge is  $0.5 \mu\text{m}$  wide and  $5 \mu\text{m}$  long, and are separated by a  $50 \mu\text{m}$  long slotline between the bridges. The whole structure including the finline tapers are deposited on a  $100 \mu\text{m}$  thick quartz substrate [2], [3]. The planar switch presented here was designed to operate in the frequency range of 180–260 GHz.

The superconducting switch chip is positioned at the E-plane of a rectangular waveguide, connected to a feed horn as shown in Fig. 2. The RF signal injected from one end of

the chip will either be re-transmitted towards the other end of the chip or reflected back to the input port, depending on the state of the switch. A superconductor-insulator-superconductor (SIS) device designed to operate in the same frequency range is placed after the switch chip to detect the transmitted RF power. The detail of the SIS detector chip can be found in [4]. Both the switch and the SIS detector chip are housed within a split aluminium block, which is mounted on the cold plate of a Gifford-McMahon (GM) coolers to cool both the chips down to cryogenic temperature (4.2 K).

The NbN bridges were alternated between the superconducting (off) and the normal (on) states by applying a bias current along the parallel-bridges through aluminium bond wires, causing them to become normal when the bias current exceeds the critical current ( $I_c$ ) value. In each case, the incoming RF signal sees two substantially different complex impedance states, hence will either pass through the transmission line with negligible loss or reflected back with high return loss [5]. By comparing the tunnelling current across the SIS device in each state, we can obtain the response of the switch [6].

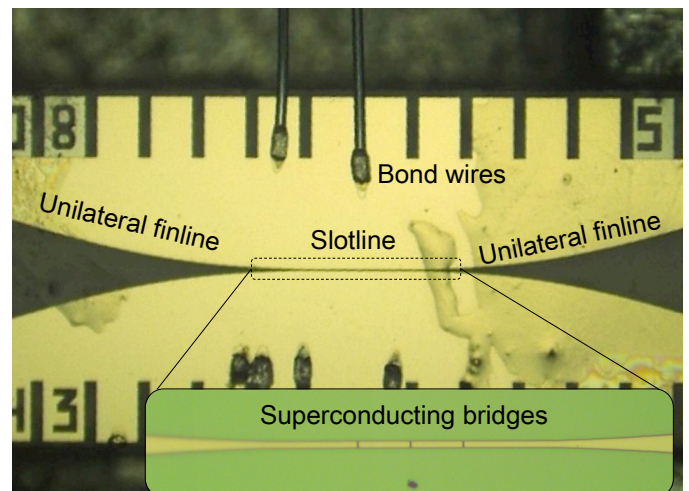


Fig. 1. A planar superconducting switch chip comprising three NbN bridges deposited across the slotline section of a back-to-back unilateral finline taper.

## II. TRANSMISSION LINE MODEL OF THE SWITCH

Using a simple model where the transmission line is shunted by a single load resistance to represent the impedance of the NbN bridge as depicted in Fig. 3 (a), one can show that the voltage transmission and reflection coefficient is given by

$$\tau = \frac{2Z_L}{Z_0 + 2Z_L} \quad \text{and} \quad \Gamma = \frac{-Z_0}{Z_0 + 2Z_L}, \quad (1)$$

where  $Z_0$  is the characteristic impedance of the transmission line and  $Z_L$  is the load impedance of the bridge. For a triple cascaded bridge model shown in Fig. 3 (b), we need to take into account the interaction between the loads. For example, to calculate  $\tau_1$  at  $z = 0$ , we need to first obtain the effective input impedance of  $Z_{L2}$  and  $Z_{L3}$  transformed by a transmission line of length  $d$  and  $2d$  respectively, where  $d$  is the distance between two bridges. The input impedance at a certain distance  $l$  from the load can be found by using

$$Z'_L(l) = Z_0 \frac{1 + \Gamma(l)}{1 - \Gamma(l)}, \quad \text{where} \quad (2)$$

$$\Gamma(l) = \frac{-Z_0}{Z_0 + 2Z_L} e^{-i2\beta l}. \quad (3)$$

The total impedance seen by the incoming signal at  $z = 0$  is therefore the product of three parallel loads. Replacing  $Z_L = Z_{z=0}$  in Eq. 1, and repeat the same calculation for  $z = d$  and  $z = 2d$ , we can therefore obtain the output voltage transmission and reflection coefficient for the complete three bridges model.

The impedance of the planar bridges is given by  $Z_L = R_s + i\omega L$ , where  $R_s$  is the resistive part of its surface impedance,

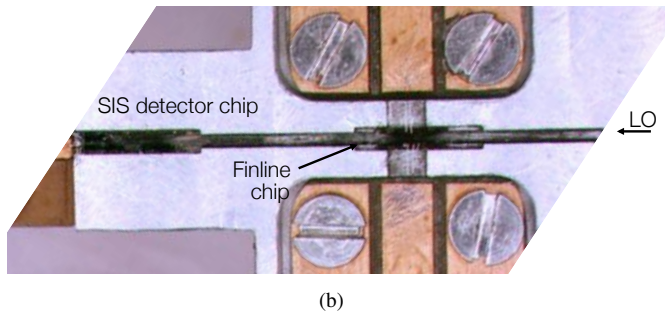
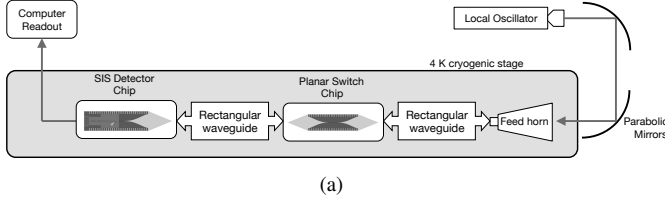


Fig. 2. (a) Experimental setup for measuring the response of the superconducting on/off switch using an SIS device as direct power detector. (b) Both the SIS detector chip and the switch chip are supported across the E-plane of a rectangular waveguide via the grooves in the waveguide wall. Two copper lines and bond wires are used to supply the bias current that switch the bridges between the superconducting and the normal state. The RF signal from the feed horn is coupled to the slotline and the bridges via a unilateral finline taper, and re-radiated towards the SIS detector chip via a similar finline taper.

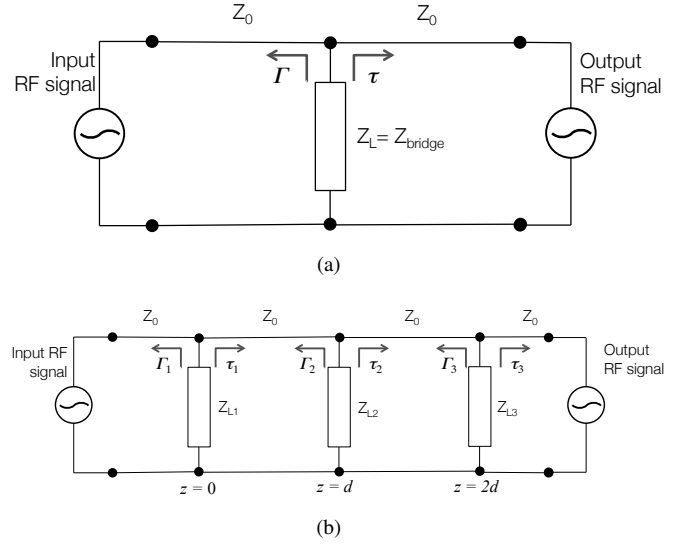


Fig. 3. (a) A simple transmission line model depicting a transmission line shunted with a load i.e., the impedance of the NbN bridge. (b) A similar circuit model with three shunted bridges.

and  $L = L_g + L_k$  where  $L_g$  is the geometric inductance and  $L_k$  is the kinetic inductance of the bridges [7]. The kinetic inductance has a significant value only in the superconducting state, whereas  $R_s = R_N$ , its thin film normal resistance in the normal state, and  $R_s \approx 0$  in the superconducting state. The value of these parameters can be approximated by:

$$R_N = \frac{\rho l}{wt}, \quad (4a)$$

$$L_g \cong 0.2l \left[ \frac{1}{2} + \ln \left( \frac{2l}{w+t} \right) + 0.11 \left( \frac{w+t}{l} \right) \right] \mu\text{H}, \quad (4b)$$

$$L_k = \mu_0 \frac{l\lambda_L}{w} \coth \frac{t}{\lambda_L}, \quad (4c)$$

where  $\rho$  is the resistivity of the superconductor,  $\lambda_L$  is the London penetration depth, and  $w, l$  and  $t$  is the width, length and thickness of the superconducting strip respectively. For an RF signal at an angular frequency of  $\omega = 2\pi f$ , the impedance at superconducting and normal states are therefore:

$$Z_{off} = i\omega(L_k + L_g), \quad \text{and} \quad (5a)$$

$$Z_{on} = R_N + i\omega L_g, \quad (5b)$$

where  $Z_{off}$  and  $Z_{on}$  are the impedance of the bridge at the superconducting and the normal states respectively. For example, using  $\rho = 140 \mu\Omega\text{cm}$ ,  $\lambda_L = 200 \text{ nm}$ ,  $d = 50 \mu\text{m}$  and  $Z_0 = 75 \Omega$  for a  $5 \mu\text{m}$  wide slotline on a  $100 \mu\text{m}$  thick quartz, we estimate that the power ratio  $D_P = \tau_{on}^2 / \tau_{off}^2 \approx 12.7 \text{ dB}$  at  $245 \text{ GHz}$ .

## III. PRELIMINARY EXPERIMENTAL RESULTS

Fig. 4 shows the DC current-voltage (IV) curves of the SIS device measured at  $245 \text{ GHz}$ . The grey lines plot the pumped IV curves of the switch biased below  $I_c$ , and the black lines for the case when the switch is not superconducting. The changes

in the level of the tunnelling current across the first photo step (approximately from 0.7–1.0 mV) is significant. When the bridges are superconducting, they effectively short (apart from the small value of inductance) the transmission line. The RF power coupled to the SIS devices is therefore significantly attenuated. On the other hand, when the bridges are biased above  $I_c$ , the complex impedance of the bridges shifts from low to high value. The incoming signal can therefore pass through with minimum loss, resulting in the increase of power detected by the SIS device since  $Z_L \gg Z_0$ .

The difference in the power transmission between the switch-on and switch-off state were found to be approximately 13 dB at 245 GHz on the first photon step region. This switching ratio between the on and the off state is measured as the change in the level of tunnelling current with reference to the leakage current measured from the unpumped curve. We use only the first photon step for this calculation, because the SIS device is most sensitive and as shown in Fig. 4, the power ratio remains relatively flat across the first photon step as well. It is worthwhile noting that the increase in the power ratio at the second photon step shown in Fig. 4 is misleading as the measured current is closed to the noise floor (leakage current) when the switch is closed and the SIS response is highly nonlinear here.

Comparing this with the estimated power ratio from Sec. II, we can see that the measured value is very closed to the estimated value. This is surprising given that we are calculating only the response of the switch in Sec. II, whereas the measured results here have the influence from the response of the detector as well. An SIS device is a nonlinear device and it has a frequency dependent power coupling behaviour as shown in Fig. 5, which could change from approximately linear to highly polynomial.

Furthermore, the simple transmission line model does not take into account the fringing effect of the various electromag-

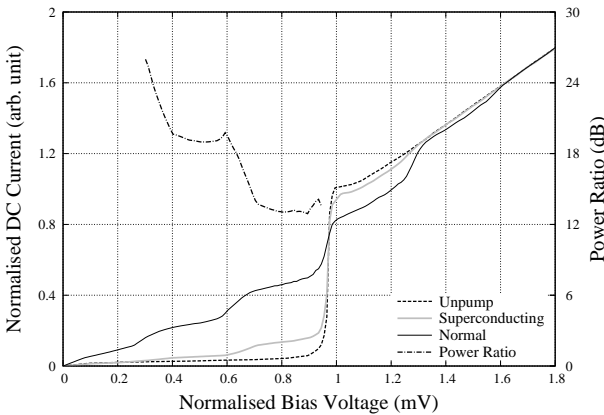


Fig. 4. The normalised DC pumped IV curves of the SIS devices under the illumination of the RF source. The grey curves show the tunnelling current measured across the SIS device when the bridges are superconducting, and the black curves for the bridges biased to the normal state. The unpumped curves are shown as dashed line for reference. The power ratio between the switching states are shown above the IV curves as dot-dot-dash line.

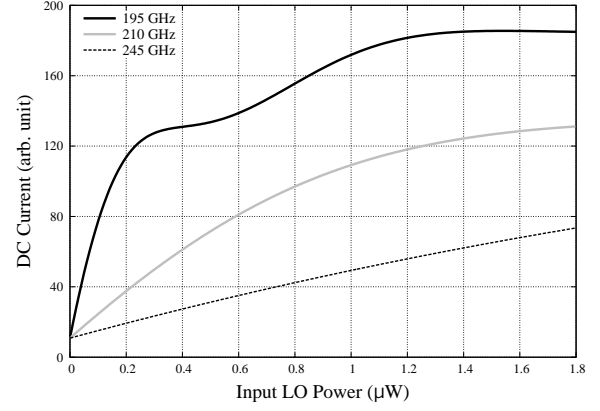


Fig. 5. The change of the level of DC tunnelling current of the SIS device biased at a fix voltage in response to the change in input power at different RF frequencies.

netic structure of the switch, especially the slotline. The field strength of a slotline is not perfectly confined between the two parallel electrodes, where a small part of it is fringed above and below the slotline. This fringing field, albeit containing only a small amount of the total power, would effectively bypassed the bridges, and weaken the effect of the bridges especially in the case where the superconducting bridge should short the slotline completely. Therefore, it could be misleading to use a simple transmission line model to estimate the power ratio for comparison with the actual measured data.

A more accurate method to simulate the behaviour of the switch would be to use a 3-D electromagnetic simulator to fully model both the switch and the SIS detector chip, and run a quantum mixing code to calculate the power coupling response of the SIS device. In our case, we use Ansys High Frequency Structure Simulator (HFSS) for the electromagnetic modelling of the chips, to include both the fringing and the superconductivity effect. The complex conductivity of the NbN film is calculated using the standard Mattis-Bardeen equation in the extreme-anomalous limit [8], and applied to a Perfect Electrical Conductor (PEC) medium in the HFSS model using a sextic polynomial function. For estimating the power coupling of the SIS detector, we use SuperMix, a quantum mixing software package developed at Caltech [9], to reproduce the pumped IV curves. The HFSS calculated scattering parameters of both the switch and the SIS detector chip were imported into SuperMix to form a complete model of our experimental setup.

Fig. 6 shows the simulated pumped IV curves of the SIS detector when the switch is swap from the superconducting state to the normal state, along with the unpumped curves for references. Since the RF optic components such as the sub-millimetre horn and the parabolic reflectors are not included in the model, we estimate the RF input power by calibrate the pumped current at normal state to the measured pumped level. The scattering parameter of the normal switch is then replaced with a superconducting switch to calculate the pumped level at superconducting state, and thereby estimate the power

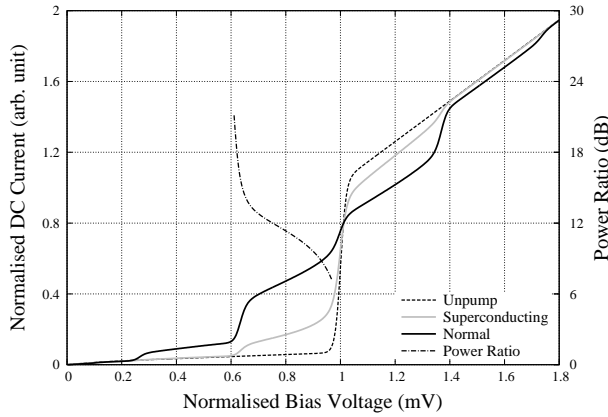


Fig. 6. The SuperMix simulated DC pumped and unpumped IV curves of the SIS devices at 245 GHz with different switch configurations. The power ratio between the switching states are shown across the first photon step region as dash-dot-dash line.

difference between the two states. As shown in Fig. 6, using this model, we managed to reproduce the IV curves very closely resemble to the measured IV curves. The power ratios are estimated at about 11 dB at  $f_{RF} = 245$  GHz, which are in fact very closed to the measured values ( $\sim 13$  dB at 245 GHz).

#### IV. CONCLUSION

We have demonstrated the successful operation of a planar on/off switch comprising three NbN bridges deposited across the slotline section of a back-to-back finline chip. Using an SIS device as a direct power detector, we measured an increase of transmitted power of about 13 dB when the switch is biased from superconducting to normal state. We have also presented two theoretical models to study the behaviour of the switch, and we managed to reproduce the IV curves and the dynamic range that are compatible with the measured results.

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