Experimental Investigation of a Twin-Bridges Superconducting Switch

Boon-Kok Tan*‡, Ghassan Yassin*, Faouzi Boussaha† and Christine Chaumont†

*Department of Physics (Astrophysics), University of Oxford, Keble Road, Oxford OX1 3RH, UK

†Observatoire de Paris, Pôle Instrumental-GEPI – 77 Avenue Denfert-Rochereau, 75014 Paris, France.

‡Contact: boonkok.tan@physics.ox.ac.uk, phone +44 1865 273 303

***Abstract*—We present the design and some preliminary measured results of a planar superconducting on/off switch comprising two niobium nitride (NbN) bridges deposited across the slotline section of a unilateral finline. The two bridges are separated by a distance of λ/4, such that the superconducting impedance of the bridges could be cancelled out at the resonance frequency. Both the NbN bridges were switched from the superconducting state to the normal state via a bias current exceeding the critical current of the NbN film. A millimetre wave source calibrated with a terahertz power meter is used to illuminate the switch, and the response of the switch in each state was measured using a superconductor-insulator-superconductor (SIS) chip as a direct detector. Preliminary measured results agreed generally well with our simulations, especially when the multiple wave reflection effect is included in our model.**

I. Introduction

A static superconducting on/off switch that can be easily integrated as part of the planar detector circuit would simplify significantly the design of a millimetre and sub-millimetre large format receiver array. An important example is to form a planar phase-switching circuit using a pair of switches, replacing the rotating half-wave plate or rotating waveguide that often are bulky and consist of moving parts. This is particularly useful for the construction of a highly sensitive pseudo-correlation polarimeter used to measure the B-mode polarisation signal of the Cosmic Microwave Background [1], [2]. The superconducting on/off switch can also be used to form an on-chip modulator to reduce the $1/f$ noise of an astronomical receiver.

II. Resonantly-tuned Twin-Bridges Superconducting Switch

In previous papers [3], [4], [5], we have presented the design and the measured performance of a 220 GHz superconducting on/off switch comprising a number of niobium nitride (NbN) bridges deposited across a slotline. Here, we exploited the strongly current-dependent complex impedance of the NbN film near its critical current value to operate the bridges as a switch. This binary change of impedance can be instigated by applying a DC bias current across the bridges. This way, any incoming RF signal would see two substantially different complex impedance states, hence will either pass through the transmission line with minimal loss or reflected back to the input port with high return loss [6].

The complex impedance of a superconducting bridge is composed of two parts: R_s, the resistive part of its surface impedance, and the inductance part $L = L_g + L_k$ where L_g is the geometric inductance and L_k is the kinetic inductance. The kinetic inductance arise only in the superconducting state where $R_s \approx 0$. In the normal state $R_s = R_N$, its thin film normal resistance. Mathematically,

$$Z_S = i\omega(L_k + L_g), \quad \text{and} \tag{1a}$$

$$Z_N = R_N + i\omega L_g, \tag{1b}$$

where $\omega = 2\pi f$ is the angular frequency of the incoming RF signal, and Z_S and Z_N are the impedance of the switch at the superconducting and the normal states respectively.

For an ideal switch, the bridges should has an impedance closed to zero in one state, and an impedance approaching infinity in another state. However, even with a highly resistive superconducting film such as niobium titanium nitride (NbTiN) or NbN films, the normal resistance is still finite for a strip with a certain realistic geometry. On the other hand, at very high angular frequency, the superconducting kinetic inductance could induce a very high complex impedance that is closed to this normal resistance value. Therefore, the switching ratio (i.e., the difference in power transmission between the two states) is limited primarily by the properties of the available superconducting material.

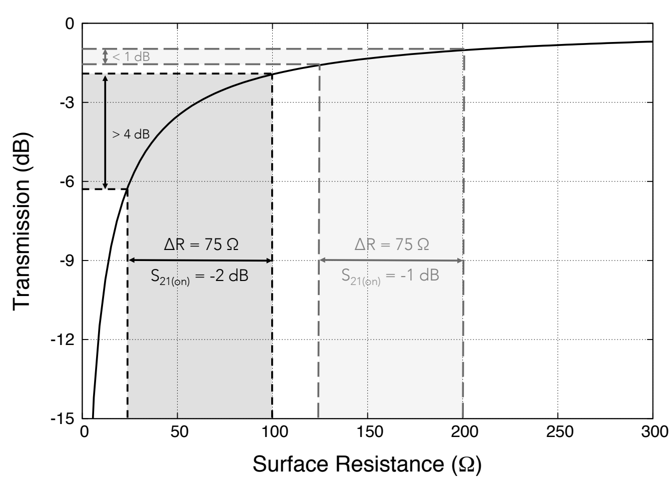


Fig. 1. The nonlinear relation between the surface resistance of a superconducting bridge shunting a slotline and its power transmission characteristic.

In previous attempts, we employed a number of short bridges across the slotline, instead of a single-shunting strip, to manoeuvre the total impedance of the switch at both states. This concept is illustrated in Figure 1, which plots the nonlinear relation between the surface impedance of a superconducting strip across a slotline and its power transmission characteristic. As can be seen, by halves the surface impedance value, the difference in power transmission between the superconducting and the normal state could be improved by several dB level. However, a fundamental disadvantage of this solution is that the employment of multiple bridges unavoidably decrease the RF transmission when the switch is closed, where the insertion loss S_{21} is now reduced from -1 dB to -2 dB.

A potentially much more effective solution to improve the switching ratio without affecting the power transmission characteristic of the switch is by creating a parallel resonant circuit using a twin-bridge tuning structure. Here, a second NbN bridge is placed a quarter-wavelength away from the first NbN bridge, so that the complex impedance of the first bridge is conjugated by the presence of the second bridge, and therefore cancelling out the unwanted superconducting inductance. In this case, the incoming RF signal would propagate through the transmission line unimpeded, since the bridges are virtually disappear now. On the other hand, when the bridges are in the normal state, the bridges become a low resistive load and the incoming wave will be reflected with minimal ohmic losses.

Figure 2 shows the predicted power transmission in both superconducting and normal state for a switch comprising two 50 nm thick NbN bridges (5 μm $\times$ 2 μm) separated by a 300 μm long slotline (5 μm width), simulated using Ansys High Frequency Structure Simulator (HFSS). As can be seen, the power transmission near 235 GHz is closed to 0 dB when the bridges are superconducting. At this central frequency, the switching ratio is closed to 8 dB, and decreases only gradually away from the resonance frequency. Although this resonance-bridges design is inherently narrow band at about 10–15 GHz, but it minimise the transmission losses significantly compared to the previous multi-bridges design. Hence, it would suit well with applications that do not require ultra-wide operational bandwidth, such as astronomical observations where the spectral line position is well-known.

III. Preliminary Results

Based on this idea, we fabricated a series of superconducting on/off switch chips with different resonance frequencies in the range of 200–260 GHz. They comprise two NbN bridges of 2 μm width deposited across a 5 μm wide slotline, supported by a 100 μm quartz substrate. The NbN bridges are modulated between the superconducting and the normal states via a DC current that alternate above and below the NbN critical current value. The RF signal is fed to the device via a unilateral finline taper, as shown in Figure 3, and transmitted through the switch via another similar taper. The chip is housed within a rectangular waveguide along the E-plane, with the front end of the waveguide block connected to a millimetre horns, as shown in Figure 4 and 5. The RF signal from a local oscillator (LO) is coupled to the horn with a pair of parabolic mirror and a beam splitter. A THz power meter is placed after the beam splitter to monitor the strength of the LO output signal to ensure the consistency of the power level across the measured bandwidth. The transmitted signal through the switch is measured at the other end by observing the pumped DC current-voltage (IV) curves of a superconductor-insulator-superconductor (SIS) chip, placed several millimetre away from the switch chip along the same rectangular waveguide

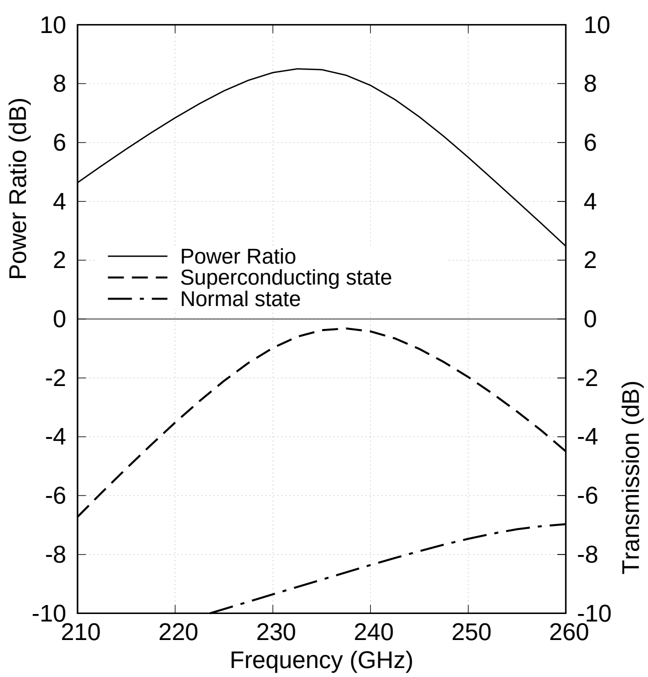


Fig. 2. The response of a superconducting on/off switch with two identical 50 nm thick NbN bridges separated by a quarter wavelength long slotline.

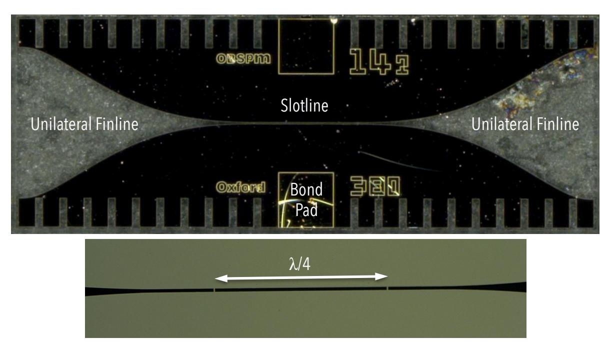


Fig. 3. A planar superconducting switch chip comprising two resonantly-tuned NbN bridges deposited across the slotline section of a back-to-back unilateral finline taper.

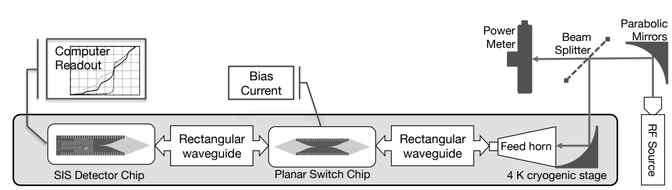


Fig. 4. Experimental setup for measuring the response of the superconducting on/off switch using an SIS device as a direct power detector.

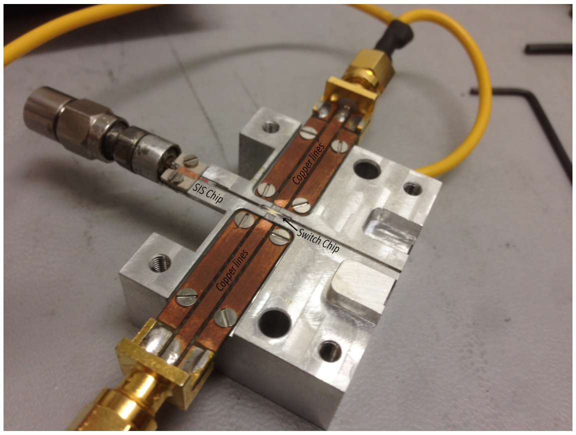
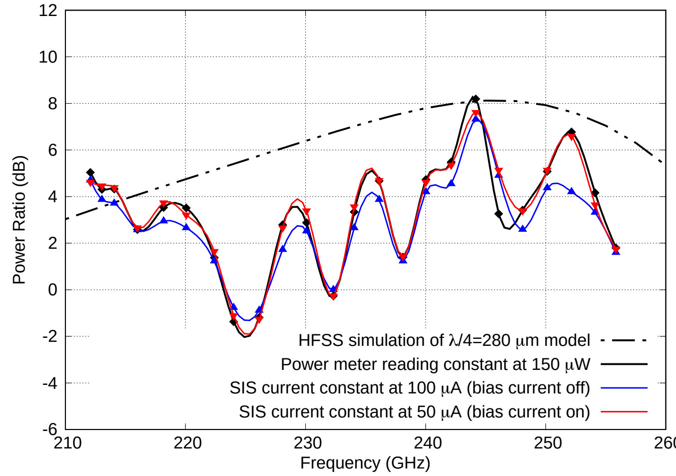


Fig. 5. Both the SIS detector chip and the switch chip are supported across the split-plane of a rectangular waveguide with a set of deep grooves on each side of the waveguide wall. The bias current for the switch is supplied through two copper line with bond wires connecting the copper strip to the switch's electrode. The SIS device is biased using a copper line and bond wires from the rear of the block.

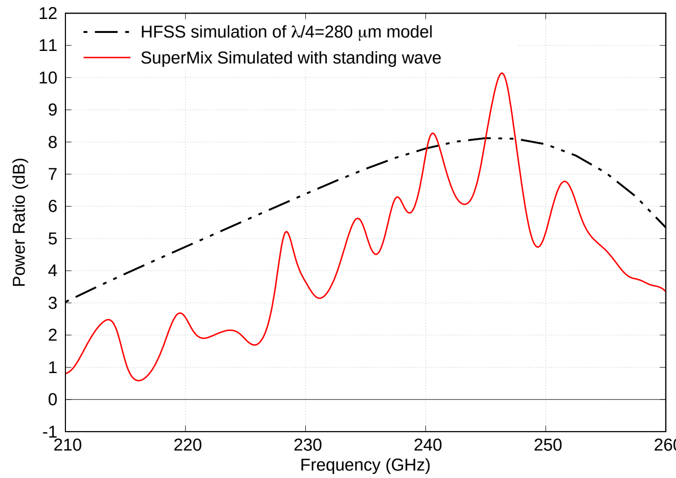
channel. The detail of the SIS detector chip can be found in [9].

In Figure 6, we show the measured responses of a NbN switch with $\lambda/4$ = 300 μm, in the frequency range of 210–260 GHz. It is clearly seen that the pumping levels of the SIS device changed by a few dB when the switch is alternated between the superconducting and the normal state. The highest switching ratio was measured at about 8 dB level, consistent with the HFSS prediction albeit a shift of frequency which appears to correspond to a twin-bridges design where the separation distance is 280 μm instead of 300 μm. However, it hard not to notice that the switching ratio varies periodically with frequency, although the general trend of the gradual decrease away from the central frequency is observed. We suspect that this periodically variation is caused by the existence of standing waves established by multiple wave reflections between the switch chip and the SIS detector chip. In our current setup, both the chips were fabricated on a relatively thick (100 μm) quartz substrate, and both the chips do not have matching notches to taper the impedance mismatch between the unloaded waveguide and the chips.

To further investigate the interaction between the switch chip and the SIS device, we used SuperMix, a quantum mixing software package developed at Caltech [10]. The SuperMix model was formed by cascading the HFSS calculated scattering parameters of both the switch (in either state) and the SIS detector chip, along with a section of empty waveguide 12 mm long (estimated for the distance between the chips) inserted between the two chips. This allow us to estimate the pumping level of the SIS device when the switch is alternated between the superconducting and the normal state, taking into account the frequency-dependent power coupling behaviour of the SIS device. Figure 6 (b) shows the result of this simulation, and it can be seen clearly now that a periodic dependence does exist if the empty waveguide is included in the model. The general behaviour of the predicted switching curve also matches very well to the measured one. This therefore reaffirm the effect of standing waves that masked the actual behaviour of the switch.



(a)



(b)

Fig. 6. (a) The power ratio measured from the SIS IV curves at a fixed bias point when the switch is alternated between superconducting and normal state. The solid black curve shows the power ratio variation with the LO input power fixed at 150 μW, overplotted with the HFSS predicted behaviour with the distance between the two NbN bridges at 280 μm. The blue and red curves show the similar power ratio variation, with the blue curve representing the case where the SIS tunnelling current (at the fixed bias point) is maintained at 100 μA level when the bias current to the switch is disconnected; while the red curve for the case where the tunnelling current is fixed at 50 μA when the biasing to the switch is on. All three measurements show an almost identical switching behaviour. (b) The power ratio variation of the switch estimated by the SuperMix model, including a section of empty waveguide between the two chips. The periodic variations and the peak of switching ratio near 245 GHz is highly resemblance of the behaviour measured experimentally.

Despite the issue with the standing wave, we have demonstrated experimentally that the resonantly-tuned superconducting bridge design can be used as an efficient on/off switch in millimetre circuits. The general behaviour, such as the power transmission when the bridges are superconducting is higher than the normal state, as well as the gradual roll-off away from the resonance frequency, follow closely the trend predicted by our calculation. Works are currently underway to minimise the multiple reflection effect by reducing significantly the distance between the two chips, and potentially fabricating both the switch and the detector circuit on the same chip.

IV. CONCLUSION

We have presented the design and the measured responses of a resonantly-tuned planar superconducting on/off switch comprising two NbN bridges deposited across the electrodes of a back-to-back finline chip. We simulated the performance of these resonantly-tuned superconducting switches using 3-D electromagnetic package, and the simulation model shows that at resonance, it has close to unity transmission while retaining relatively large switching ratio across the designated bandwidth. Using an SIS device as a direct power detector, we have measured a maximum switching ratio of $\sim$8 dB at 245 GHz, although the typical power ratio varies considerably across the $210-260$ GHz due to the standing wave interaction between the switch and the SIS chip. Nevertheless, we managed to reproduce the measured results using SuperMix, taking into account the coupling behaviour of the SIS chip and the effect of an empty waveguide between the chips. The simulated result agrees very well with the measurements, establishing our understanding that the performance deviated from the intended design was caused by the introduction of unwanted standing waves. The measurement of the remaining devices within the same batch is still on going and works are underway to improve the measurement setup so that we can measure the response of the switch more prominently without the influence of the standing waves.

REFERENCES

[1] P. K. Grimes, G. Yassin, L. S. Kuzmin, P. D. Mauskopf, E. Otto, M. E. Jones, and C. E. North, "Investigation of planar switches for large format CMB polarization instruments," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 6275 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, July 2006.

[2] G. Yassin, L. S. Kuzmin, P. K. Grimes, M. Tarasov, E. Otto, and P. D. Mauskopf, "An integrated superconducting phase switch for cosmology instruments," *Physica C Superconductivity*, vol. 466, pp. 115–123, Nov. 2007.

[3] B.-K. Tan, G. Yassin, E. Otto, and L. Kuzmin, "Experimental investigation of a 220 ghz superconducting switch with multiple nano-bridges," in *Millimeter Waves and THz Technology Workshop (UCMMT), 2015 8th UK, Europe, China*, pp. 1–4, 2015.

[4] B.-K. Tan, G. Yassin, E. Otto, and L. Kuzmin, "Investigation of the Dynamic Range of Superconducting Nano-Bridge Switches," in *Twenty-six International Symposium on Space Terahertz Technology*, 2015. .

[5] B.-K. Tan, G. Yassin, E. Otto, and L. Kuzmin, "Experimental Investigation of a Superconducting Switch at Millimetre Wavelengths," *IEEE Transaction on Terahertz Science and Technology*, pp. 121–126, jan 2016. .

[6] B.-K. Tan, G. Yassin, L. Kuzmin, E. Otto, H. Merabet, and C. North, "A Superconducting Millimetre Switch with Multiple Nano-Bridges," in *Twenty Fifth International Symposium on Space Terahertz Technology*, Apr. 2014.

[7] V. I. Belitskii, M. A. Tarasov, S. A. Kovtoniuk, L. V. Filippenko, and O. V. Kaplunenko, "Low noise completely quasioptical SIS receiver for radioastronomy at 115 GHz," *International Journal of Infrared and Millimeter Waves*, vol. 13, pp. 389–396, Apr. 1992.

[8] P. Grimes, *Design and analysis of 700 GHz Finline Mixers*. PhD thesis, University of Cambridge, United Kingdom, 2006.

[9] B.-K. Tan, F. Boussaha, C. Chaumont, and G. Yassin, "A 220 GHz Finline Mixer with Ultra-Wide Instantaneous Bandwidth," in *Twenty Sixth International Symposium on Space Terahertz Technology*, Mar. 2015.

[10] J. Ward, F. Rice, G. Chattopadhyay, and J. Zmuidzinas, "Supermix: A flexible software library for high-frequency circuit simulation, including sis mixers and superconducting elements," in *Proceedings, Tenth International Symposium on Space Terahertz Technology*, pp. 269–281, 1999.