Investigation of the Dynamic Range of Superconducting Nano-Bridge Switches

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***Abstract*—We present the design of planar superconducting on/off switch comprising a number of high normal resistance nano-bridges deposited across a the slot of a unilateral finline. We have simulated the performance of this device and have shown that it has a much larger dynamic range than a single nano-bridge fabricated from the same material (Niobium Nitride, NbN). The response of a single bridge device was measured either directly using a terahertz power meter or by using superconductor-insulator-superconductor (SIS) device as direct detector. In either method, we have demonstrated good agreement between simulations and measurements, and therefore confirmed the integrity of our analysis of the device performance. We have recently designed and fabricated multiple nano-bridges superconducting switches using 50 μm thick NbN film. The measurement of these devices is currently in progress and we expect to report the results in the forthcoming ISSTT conference in March.**

I. Introduction

A planar superconducting on/off switch that can be used to modulate millimetre and sub-millimetre signal with high switching speed is important for various astronomical instruments operating in this wavelength regime. It offers a potentially much more efficient and elegant solution against the traditionally used rotating quasi-optical or waveguide half-wave plates and Faraday rotators [1]. This is particularly important for constructing ultra-sensitive polarimeter for measuring the polarisation state of the Cosmic Microwave Background (CMB) signals. Another important application is the Bolometric Interferometry instruments where the beams are combined at RF frequencies. An important advantage of a planar nano-switch design is that it allows the modulator to be easily integrated into the detector circuit, offering a compact and low power consumption solution, and therefore enabling the construction of a large format focal plane array.

II. Planar Superconducting On/Off Switch

In previous papers [2], [3], [4], [5], we have demonstrated that a nano-switch integrated across the gap of a unilateral finline can provide an on/off switching operation as the nano-bridge is switched between the normal and superconducting state using a step current source.

Our superconducting on/off switch is designed to operate in the frequency range of 180–260 GHz. It comprises NbN nano-bridges of 0.5 μm width deposited across a 5 μm wide unilateral finline slot, supported by a 100 μm quartz substrate. The RF signal is fed to the device via a back-to-back unilateral finline taper, as shown in Figure 1. The finline chip is positioned at the E-plane of the waveguide, connected to two millimetre horns via the waveguide transition pieces, arranged in a similar back-to-back optical layout, as shown in Figure 2. The local oscillator (LO) signal is fed from one end, and the transmitted signal is measured at the other end.

The NbN nano-bridges are modulated between the superconducting (on) and the normal (off) states by applying a square-wave bias current across the nano-bridges, causing the device to switch from the superconducting state to the normal state when the bias current exceeds the critical current value. In previous experiments, the transmitted signal was read by observing the pumped I-V curve of a superconductor-insulator-superconductor (SIS) device [5]. On this occasion, this was replaced with a free-space absolute terahertz power-energy meter from TK Instruments to measure the difference in the transmitted output power in each state, and therefore obtain the response of the switch to the LO signal.

III. Preliminary Results

The idea of the superconducting nano-switch is that the transmission line presents low input impedance to the incoming wave when the nano-bridge is in the superconducting

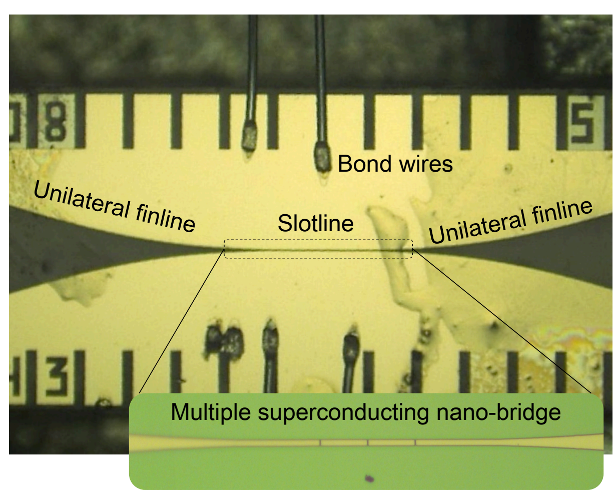

Fig. 1. A planar phase switch demonstrator comprising three superconducting nano-bridges deposited across the slotline section of a back-to-back unilateral finline taper.

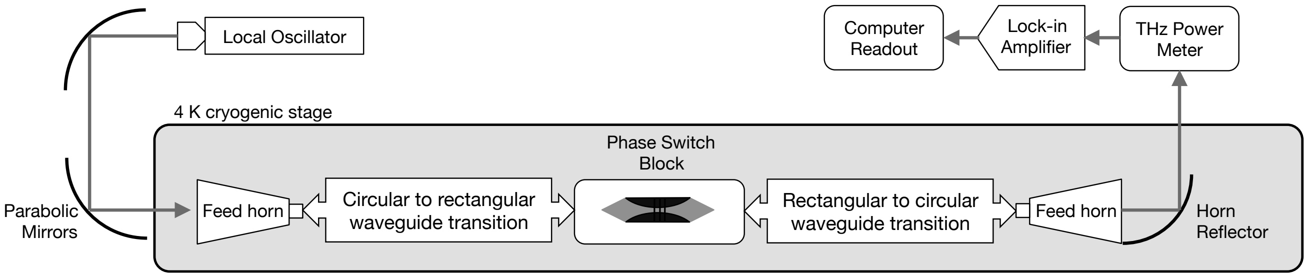

Fig. 2. Experimental setup for measuring the response of the superconducting on/off switch using a THz power meter.

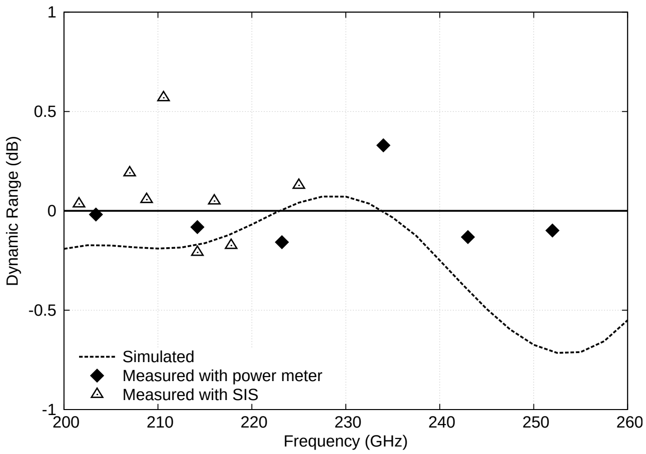

Fig. 3. Measured responses of a superconducting switch with 20 nm thick NbN nano-bridge using both the setup with THz power meter (diamond) and the SIS device (triangle) as power detector. The HFSS simulated response of the same device show a similar dynamic range and switching behaviour as the measured results.

state (switch on) and a high input impedance when the nano-bridge in the normal state. The dynamic range of the switch is therefore primarily determined by the ratio of the normal resistance to the kinetic reactance. A high performance nano-switch therefore will have a high normal resistance (normal state) and a small kinetic inductance (superconducting state).

We have previously fabricated several superconducting on/off switches with only one nano-bridge of 20 nm thick across the slotline. Figure 3 shows the measured response of the device measured using the new setup shown in Figure 2, along with the previously measured results using the SIS device as direct detector. As can be seen, the measured dynamic ranges are rather consistent within ± 0.5 dB, and more importantly agree with the responses predicted by the High Frequency Structure Simulator (HFSS) model.

However, the dynamic range of these devices was poor since the ratio of the normal resistance to the kinetic impedance was not high enough. This is because when the nano-bridge was in superconducting state, it did not reflect the incoming signal efficiently. This can easily be seen by recalling that the impedance of a superconducting strip is determined by the resistive part of its surface impedance R_{surf}; the geometric inductance L_{geo}, and the kinetic inductance L_{kin}. The later inductance has a significant value only in the superconducting state, whereas $R_{surf} = R_N$, its thin film normal resistance in the normal state, and $R_{surf} \approx 0$ in the superconducting state. The value of these parameters are given by [6]:

$$R_N = \rho l / wt, \tag{1a}$$

$$L_{geo} = 0.2l \left[\frac{1}{2} + \ln\left(\frac{2l}{w+t}\right) + 0.11\left(\frac{w+t}{l}\right) \right] \mu\text{H}, \tag{1b}$$

$$L_{kin} = \mu_0 \frac{l\lambda_L}{w} \coth \frac{t}{\lambda_L}, \tag{1c}$$

where ρ is the resistivity of the superconductor, λ_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/LO signal at an angular frequency of $\omega = 2\pi f$, the two impedance states are thus given by:

$$Z_{sc} = i\omega(L_{kin} + L_{geo}), \quad \text{and} \tag{2a}$$

$$Z_{norm} = R_N + i\omega L_{geo}. \tag{2b}$$

For an ideal switch: in the superconducting ('switch-on') state, the nano-bridge should has an impedance of $Z_{sc} \to 0$. In this state, the load acts as a short, and any waves propagating along the transmission line are reflected. In the normal ('switch-off') state, the surface impedance is much higher ($\approx R_N$) and the nano-bridge has an impedance of $Z_{norm} \to \infty$. The switch becomes opened and the RF/LO signal will pass through the transmission line with minimum loss.

Initially, we attempted to increase the dynamic range by reducing the nano-bridge thickness down to 20 nm, hence increasing the normal resistance. But from Equation 1, we can clearly see that the kinetic inductance L_{kin} depends exponentially on t/λ_L due to the $\coth(t/\lambda_L)$ term. Decreasing the value of t/λ_L therefore gives rise to a much larger increase in the value of the kinetic inductance than in the normal resistance (which depends linearly on thickness), causing a decrease in the dynamic range. The thickness of the nano-bridges in our new devices was therefore increased from 20 nm to 50 nm so that it is now approaching the London penetration depth of the NbN film, hence reducing the kinetic inductance of the nano-bridges.

IV. High Dynamic Range Broad Bandwidth Design

An illustration of the ideas described above is shown in Figure 4 which gives the power transmission allowed by the switch as a function of the surface impedance of the nano-bridges. From the plot, it is clearly seen that the dynamic range improves with the lower surface impedance values (e.g., by

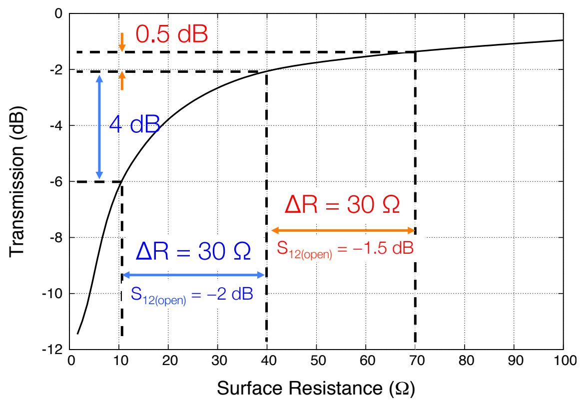

Fig. 4. The non-linear relation between the surface impedance of the nano-bridge and the power transmission.

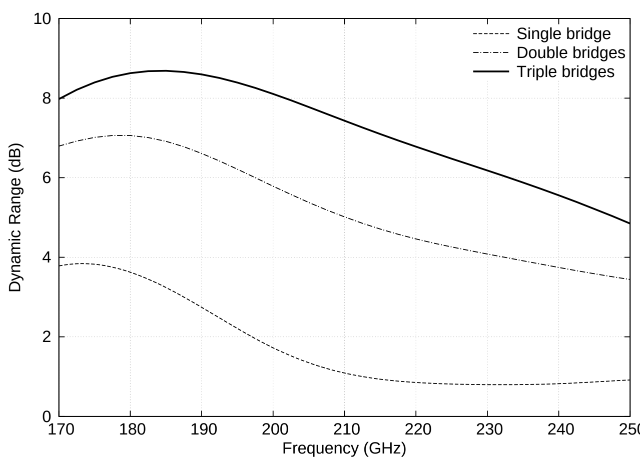

Fig. 5. The response of a superconducting on/off switch with one-, two- and three- 50 nm thick NbN nano-bridges separated with 50 μm long slotline.

increasing t), as a result of the sharp increase in the difference of impedance between the two states.

To test the idea that increasing the nano-bridge thickness improves the dynamic range, we have included a variety of designs with single, two or three nano-bridges deposited across the finline in the new fabrication batch. Multiple nano-bridge designs were introduces in order to allow the total impedance of the switches seen by the RF/LO signal at both ‘on’ and ‘off’ states to be altered, giving a degree of freedom in selecting the optimum operating point of the switches [5].

Figure 5 shows the HFSS simulated model of a single, two and three nano-bridge/s deposited in parallel to form the on/off switch. Each nano-bridge is 0.5 μm wide, 5 μm long and separated from each other by a distance of 50 μm. The nano-bridges were all formed using a 50 nm thick NbN film, and the RF/LO signals are fed and read using similar back-to-back unilateral finline taper as described before. As can be seen from the plot, the dynamic range improves almost linearly with the number of nano-bridges. The testing of these new devices is currently underway and the measured results will hopefully be reported in the forthcoming ISSTT meeting in March.

V. Twin-Bridge Resonant Tuning: A New Design Concept

A fundamental disadvantage of the nano-switch investigated above is that they require a small kinetic inductance in the superconducting state and large normal resistance in the normal state. We have shown that a large ratio of $r = {}^{R_N}/_{|L_{kin}|}$ is fundamentally difficult to achieve for given material parameters. The employment of multiple bridges improves the the dynamic range but at the same time they decrease the normal resistance since the resistances of the bridges are added in parallel. This can clearly be seen in Figure 4 as the insertion loss S_{12} decreases from -1.5 dB to -2 dB as the normal resistance is reduced by 30 Ω. One can think of ways to decrease the normal resistance of the bridges without decreasing the thickness but it is bound to make the device more complex and may result in increasing the critical current. We have already attempted to encounter this problem by creating a series RLC circuit integrated to the device in order to tune out the kinetic inductance. This however resulted in a multi-layered structure which is difficult to fabricate as a result of the parallel plate capacitor.

A much more elegant solution to increasing the dynamic range without impeding a penalty on the power transmission when the switch is open, is to create a parallel resonant RL structure by using a twin-bridge tuning design. This is largely similar to the twin-junction tuning network used for cancelling out the junction capacitance of an SIS mixer [7], [8]. Here, we employ a second nano-bridge to tune out the inductance of the first nano-bridge at a certain operating frequency. The two nano-bridges are separated by a quarter-wavelength transmission line, so that the complex impedance of one nano-bridge is equal to the complex conjugate impedance of the other nano-bridge after it is transformed by the transmission line.

For an incoming RF/LO signal near the resonance frequencies $\omega = 2\pi f_R$, the two impedance states of switch in this twin-bridge tuning design are now governed by:

$$Z_{sc} = \left[\frac{1}{i\omega L_{sc}} + \frac{1}{-i\omega L_{sc}}\right]^{-1} \rightarrow \infty, \quad \text{and} \tag{3a}$$

$$Z_{norm} = \left[\frac{1}{R_N + i\omega L_{geo}} + \frac{1}{R_N - i\omega L_{geo}}\right]^{-1} \tag{3b}$$

$$= \frac{R_N^2 + (\omega L_{geo})^2}{2R_N}, \tag{3c}$$

where $L_{sc} = L_{kin} + L_{geo}$.

One notes immediately that the switching principle of operation is now the reverse to the one employed in Section III. In this case, when the nano-bridges are superconducting, the total impedance $Z_{sc} \rightarrow \infty$, and therefore the switch becomes opened and any waves propagating along the transmission line is transmitted through unimpeded. When the nano-bridges are in the normal state, and as long as the switch impedance $Z_{norm} \leq Z_0$, the characteristic impedance of the slotline, the switch will, approximately, act as a short and reflects the incoming wave provided $R_N << Z_0$, which is not at all difficult to achieve. This reverse operation scheme therefore requires the impedance at the normal state Z_{norm} to be as

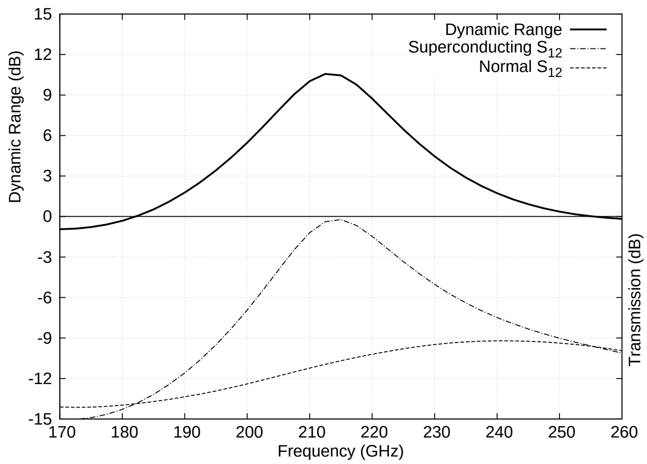

Fig. 6. The response of a superconducting on/off switch with two 50 nm thick NbN nano-bridges separated by a quarter wavelength long slotline.

low as possible. This can be done in several ways, such as increasing the width of the nano-bridges or using a low normal resistance superconducting material such as Niobium (Nb). In fact, use of a wider nano-bridge also eliminates the need for using electron-beam lithography to fabricate these devices.

Figure 6 shows the HFSS predicted dynamic range and the power transmission in both superconducting and normal state for a switch comprising two 50 nm thick NbN nano-bridge separated by a quarter-wavelength slotline, deposited across the slotline section of the back-to-back finline taper. The nano-bridge is 5 μm long and 2 μm wide now, in order to reduce the normal resistance R_N, and therefore increase the dynamic range. As can clearly be seen from the plot, at the resonance frequency of 215 GHz, the dynamic range is higher than 10 dB, while the power transmission when the switch is superconducting is approaching 0 dB. This improves significantly the power transmission of the switch and provides an ideal switch design for applications where the incoming signal is weak. It is however evident from the plot that the operating bandwidth of the resonant switch is narrower than that of the multiple bridge switch described in Section IV.

VI. Conclusion

We have presented a design of a planar superconducting on/off switch comprising nano-bridges deposited across the electrodes of a slotline. Preliminary experimental results have been presented and agree well with electromagnetic model simulations. The low dynamic range of the single nano-bridge switch was caused mainly due to its small thickness since it caused the residual kinetic inductance to be too high in the superconducting state. In this paper, we therefore proposed two solutions to improve the dynamic range of the switch, by employing multiple nano-bridges across the same slotline. By carefully choosing the separation distance between the nano-bridges, we can either design a broadband solution with slight loss of transmission or a resonant narrow band design without compromising the power transmission of the switch. In either case, we predict a dynamic range of more than 10 dB. We are currently in the process of measuring the response of the broadband design with a thicker NbN film, and the measured results shall be reported in the forthcoming ISSTT conference in March.

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