A Reflective Microwave Switch Made of Tl–Ca–Ba–Cu–O for Signal Control Applications

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Abstract—**Some high performance control applications in high temperature superconductors (HTS) require switches that can be easily integrated with transmission lines. A microwave switch in Tl–Ca–Ba–Cu–O has been developed based on driving a small bridge, embedded in a transmission line, normal via a current in an external control line. In the on-state, insertion loss was less than 1 dB over the tested range of 0.5–8.5 GHz. Isolation in the off-state exceeded 30 dB over this frequency range. Response times are on the order of a microsecond, adequate for many microwave/millimeter-wave applications such as switched phase shifters.**

I. Introduction

WITH the advent of very low loss, low dispersion transmission lines made from HTS materials (e.g., [1]–[3]), an easily insertable microwave switch would be an important adjunct component for high-performance signal control circuits. Potential applications include switched delay line phase shifters and microwave signal distribution networks. Integration of the switch in coplanar waveguides, microstrip lines and a variety of other transmission systems is possible. The device is characterized by low on-state insertion loss, good isolation and switching times on the order of a microsecond. Switching time is limited to no less than about 1 μs by thermal time constants. Many control applications do not require faster switching than this. Faster switches will require the use of Josephson junction [4] or flux flow devices (e.g., [5], [6]). Both of these switch types will suffer from poor isolation without fairly complicated circuitry. Semiconductor-based switches are more difficult to integrate with HTS materials and insertion losses are typically on the order of 2 dB. The thermal HTS switch on the other hand occupies an area smaller than 100 μm by 20 μm and provides at least 30 dB of isolation.

II. Switch Design and Structure

The thermal HTS switch is based on driving a small thin superconducting bridge into the normal state. This can be done by heating or by direct application of magnetic field. The latter approach has been used before in a low temperature superconducting (LTS) device called the cryotron (e.g., [7], [8]). There the film is driven normal by exceeding a local critical magnetic field [9]. In many of the LTS materials, this critical field to drive the superconductor normal is on the order of a few hundred Gauss or less. Considering demagnetization effects [9], it is relatively easy to exceed these critical fields with a small current in a nearby superconducting control line. The magnetic fields required to drive HTS materials normal, however, are typically very large (several Tesla). The resultant switching between a superconducting and a mixed, resistive state [9] typically does not provide much isolation. The approach chosen here is instead to drive the bridge normal by locally exceeding the superconductor's critical temperature. A normal metal control line provides heating and, in addition, a local magnetic field. Evidence presented below suggests that a flux-containing mixed state is induced by the magnetic field well before the bridge switches normal. The mixed state aids the control line heating in producing the phase transition in the bridge thus reducing total energy requirements.

The layout of the switch is shown in Fig. 1. The bridge is embedded in a 50 Ω coplanar waveguide. The TlCaBaCuO base film (on a $LaAlO_3$ substrate) is patterned with standard optical lithography (e.g., [5]) and the bridge region (about 200 μm by 10 μm) is thinned relative to the transmission line around it ($\approx$ 50-nm bridge thickness versus 300 nm for the transmission line). This reduces power requirements for driving the bridge normal by reducing the total heat load in the active area and by allowing flux motion [10]. In addition, hot spots can be confined to a small area keeping the noise low and the switch more stable. Etching and thinning are done with a Br/isopropanol solution with concentrations of 2% for etching and 0.5% for thinning. An interlevel dielectric, hard-baked negative photoresist, is placed over the HTS transmission line and a Ti–Au control line (serpentined for increased heat output and magnetic field amplitude) is formed on the next level by lift-off. A thermal insulator (photoresist or vacuum grease) is then placed over the control line in the switch area to reduce power requirements.

III. Results

Samples were first characterized by measuring $|S_{21}|$ as a function of control current at 77K. Plots of $|S_{21}|$ with

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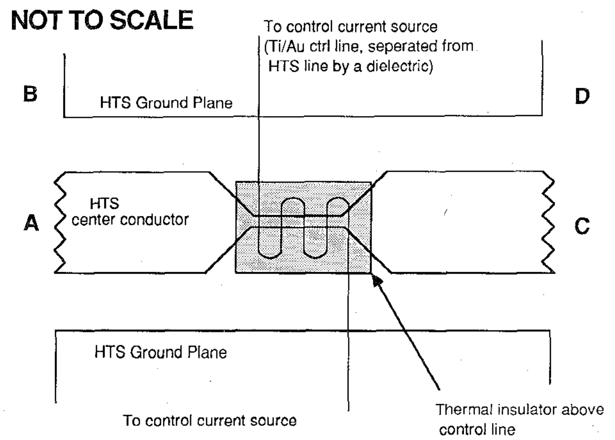

Fig. 1. Diagram of the thermal switch used in the experiments. The small bridge (100 μm by 10 μm by 50 nm) is embedded (during photolithography) in a 50 Ω coplanar waveguide. The Ti-Au control line provides heating and magnetic fields for switching, the meandering is to increase these effects. A thin dielectric separates the control line from the bridge and a thick dielectric is above the control line to slow heat loss to the LN_2 bath.

$I_{\text{control}} = 0$ mA and $I_{\text{control}} = 15$ mA are shown in Fig. 2. The control current was chosen for quick turn-off and turn-on time. This I_{control} produced enough heat to drive the bridge normal but did not raise the local temperature too high (power dissipation in the control line was about 5 mW). Incident RF power for the data described below was -10 dBm; no performance variations were noted over the available power range of -40 dBm–0 dBm (although some dependence is certainly expected for higher power levels). Note the very low insertion loss and good match while in the superconducting (on) state. Isolation of over 30 dB and nearly total reflection ($|S11| = |S22| > -1$ dB across the band in the off-state) of the incident signal are present when the switch is off. Model predictions calculated using film parameters and device geometry are also shown in Fig. 2. The predictions assume the entire bridge goes normal and that the resistivity of the normal bridge was 3.5 $\mu\Omega$-m. This resistivity value was calculated from the film's measured resistivity data and an estimated bridge temperature of 150K. The equilibrium normal bridge temperature was calculated from a simplistic heat transfer model. The circuit model used for the predictions included the above calculated normal state resistance of the bridge, capacitive coupling to the control line, control line inductance, discontinuity models for all of the transitions and some launch parasitics. Most of the deviations between measured and predicted values are due to incomplete launch modeling (parasitics estimated in previous work [11]) and relatively poor fixturing.

Switching time was measured by sending current pulses (amplitude $I_{c,pk}$) through the control line and observing the conduction behavior of the transmission line. A dc signal of 400 mV was applied across AB (see Fig. 1, input of the line) and the output voltage across CD (see Fig. 1) was monitored with an oscilloscope of 50 Ω input impedance. The results are shown in Fig. 3 (circuit at 77K). For $I_{c,pk} = 12$ mA, the switch-off time was ≈ 0.75 μs while the switch-on time was ≈ 4 μs (Fig. 3(a)). The difference is likely due to heat storage in the surroundings while the link is being heated.

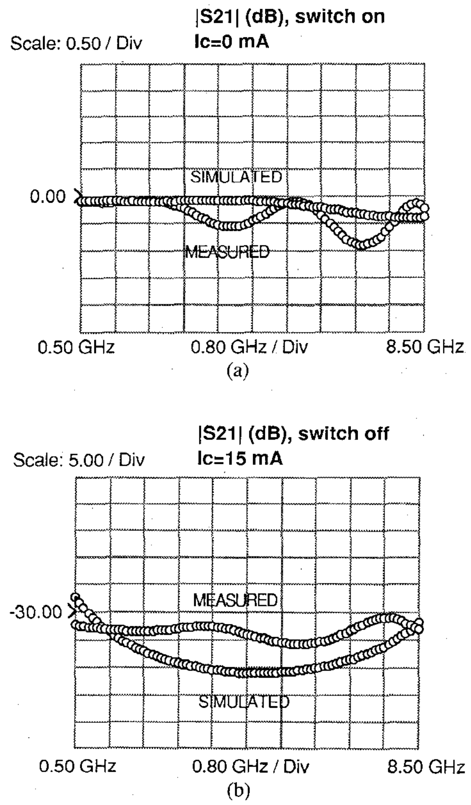

Fig. 2. Plots of measured and simulated $|S21|$ of the system shown in Fig. 1. (a) is with no control current applied (on state) and (b) is with 15 mA of control current applied (off state). Note the low on-state insertion loss and the good off-state isolation.

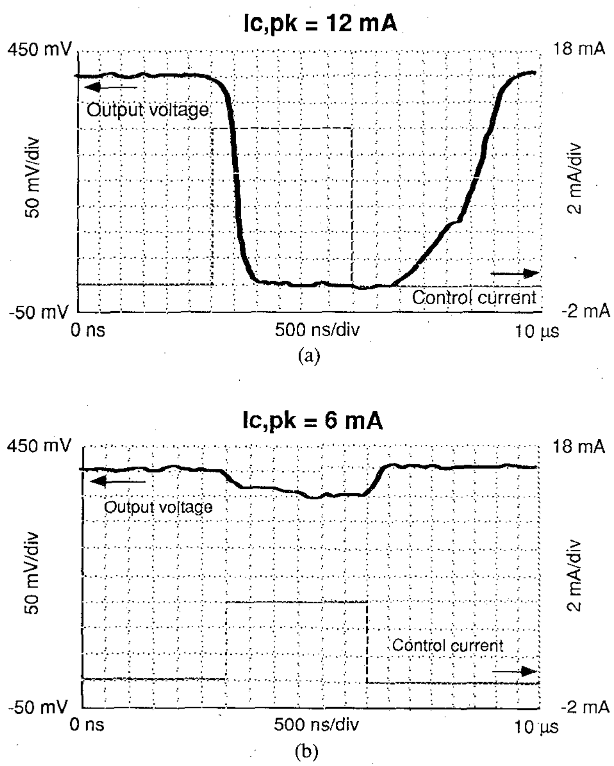

Fig. 3. Time response of the thermal switch. A 400 mV dc signal was applied across the transmission line input and the output voltage was measured. In (a) the control line was pulsed with 12 mA and in (b) the step amplitude was 6 mA. In the latter case, the bridge never goes normal, but probably enters a mixed state.

The switch-on time is a function of pulse duty-cycle as would be expected. For $I_{c,pk} = 6$ mA, the link appears to enter a mixed state [9] as shown in Fig. 3(b). The corresponding insertion loss was measured to be approximately 4 dB across the band and was observed to be stable and repeatable (to within 0.2 dB). This state is potentially attractive for leveling circuits and variable attenuators.

IV. Conclusion

We have demonstrated a thermal thin film HTS switch that is easily inserted into high performance HTS transmission lines. Signal isolation exceeded 30 dB with switch-off times < 1 μs and switch-on times < 5 μs. Through proper thermal engineering, we think the switching times can be made at least an order of magnitude lower. Insertion loss in the on state is less than 1 dB which is better than many GaAs switches used for similar applications. We believe these characteristics to be adequate for control applications including phase shifters needed for phased array radar.

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