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Comparative Study of Bolometric and Non-Bolometric Switching Elements for Microwave Phase Shifters

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COMPARATIVE STUDY OF BOLOMETRIC AND NON-BOLOMETRIC SWITCHING ELEMENTS FOR MICROWAVE PHASE SHIFTERS

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ABSTRACT

This paper compares the performance of semiconductor and high-T_c superconductor switches as they are used in delay-line-type microwave and millimeter-wave phase shifters. We compare such factors as their ratios of the off-to-on resistances, parasitic reactances, power consumption, speed, input-to-output isolation, ease of fabrication, and physical dimensions. Owing to their almost infinite off-to-on resistance ratio and excellent input-to-output isolation, bolometric superconducting switches appear to be quite suitable for use in microwave phase shifters; their only drawbacks are their speed and size.

We also discuss the SUPERFET, a novel device whose operation is based on the electric field effect in high-T_c ceramic superconductors. Preliminary results indicate that the SUPERFET is fast and that it can be scaled; therefore, it can be fabricated with dimensions comparable to semiconductor field-effect transistors.

I. INTRODUCTION

Phase shifters are an indispensable part of phased-array microwave antenna systems. There are many different realizations of phase shifters, which can be broadly divided into analog and digital types [1]. Here we confine ourselves to only digital and planar configurations. Specifically, we will discuss microstrip line phase shifters [2].

Three parameters can be altered to cause a phase shift in an electromagnetic wave traveling on a microstrip line. These are velocity [3], path length [1], and reactance [4] (or the load in a transmission line that effectively changes the group velocity). Changing the velocity or path length is straightforward. Changing reactances is more involved and it is usually so frequency sensitive that it is rarely used except where frequency-dependent phase shift is sought. Changing the wave velocity is relatively easy in a traditional waveguide; so it is used extensively with rectangular waveguides, though not in microstripline-based systems. Inducing a change in the wave velocity requires an electro-optic substrate such as GaAs, whose permittivity or refractive index can be altered by an external electric field (only recently has attention been given to this approach [5]). Routing the microwave through paths of different length (delay lines) is a practical way of inducing phase shift that we will consider in more detail.

Figure 1 shows a delay line phase shifter that uses electronic switches to route the microwave through different paths. Ideally, these switches would have an infinite off-to-on resistance ratio and would not interfere with the propagation of the microwave; also there would be no interaction between the control signal of the switch, and the microwave. In the following sections, we will discuss semiconductor and superconductor switches and we will compare their performances.

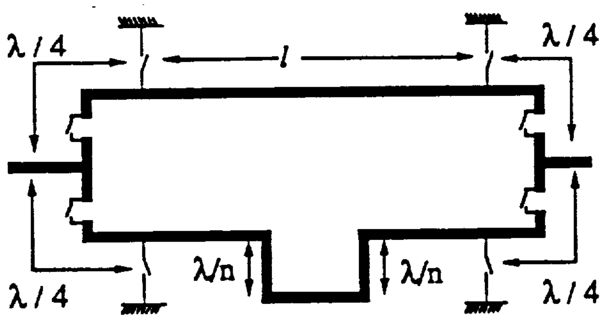


Figure 1 Delay line Phase shifter.

II. SEMICONDUCTOR SWITCHES

PIN diodes [6] and field effect transistors [7] are used as semiconductor switches in delay-line phase shifters. PIN diodes are also used as varactors in analog phase shifters, as are FETs in amplifier-type phase shifters. Dual-gate FETs [8] have become popular in analog phase shifters because a single device can both amplify and switch a signal; essentially they are dc-gain-controlled microwave amplifiers and phase shifters.

PIN Diodes. PIN diodes are extensively discussed in the literature (for example, see reference 1). They are minority-carrier devices and, therefore, their power consumptions are high. They have a storage delay time of 0.2 μs and "on" resistance of 0.5-5 Ω [9,10], but are relatively lossy with an "off" resistance of 1-4 MΩ and capacitance of 0.4-0.8 pF [9,10]. The physical dimensions of a low-power PIN diode in the unpackaged planar form is approximately 25μm x 100μm. However, since they require a biasing circuit their overall effective dimensions are much larger.

MESFETs and MISFETs. These devices have been developed extensively in recent years, and they are used in microwave monolithic integrated circuits (usually GaAs based) successfully. They are majority-carrier devices and require little power. They have an "on" resistance of 0.5-5 Ω [9,10], but are lossy with an "off" resistance of 1-40 KΩ and drain-to-source capacitance of 0.4-0.8 pF [9,10]. Their switching speed is as high as 0.1 ns. Low-power FETs in the unpackaged planar form are 100μm x 100μm. However, since they require a biasing circuit, their overall effective dimensions are much larger.

III. SUPERCONDUCTING SWITCHES

Superconductor switches that can be used in phase shifters are of the following types: (1) bolometric devices heated by light [11,12] or by an overlay polysilicon or metallic heater, (2) devices photonically controlled by laser excitation [13], (3) magnetic field effect devices controlled by the magnetic field of an inductor loop [14], (4) transverse electric field effect devices controlled by charging a gate electrode [15-21], and (5) longitudinal electric field effect devices controlled by current density [21].

Bolometric Devices. In Figure 2a, we show a phase shifter that uses superconducting-normal-superconducting switches in place of FET/diode switches. The switches are fabricated from high temperature thin films of $YBa_2Cu_3O_{7-x}$. The switches operate in the bolometric mode with the film near its transition temperature. Radiation from a light source raises the temperature higher than the film's T_c and consequently causes the film to become resistive. When the light is on the microwave signal travels past the switch; it is reflected when the light is off. To achieve the desired phase shift, the paired switches on the same side are illuminated. Figure 2b shows the predicted behavior for a phase shifter with an R_s

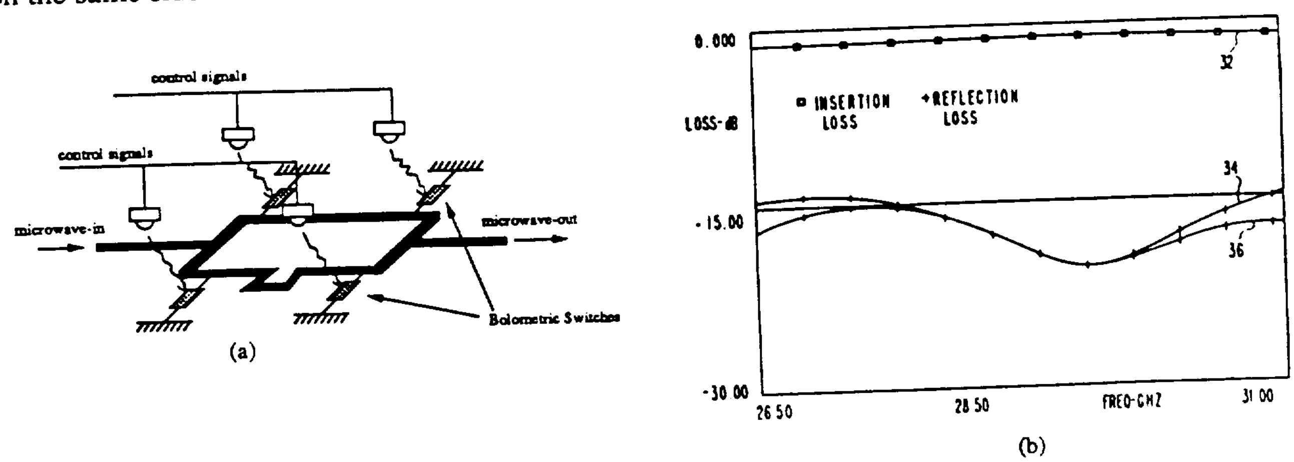


Figure 2 a) A delay line phase shifter with bolometric switches. b) Insertion and reflection losses of a delay line phase shifter that uses superconducting switches.

value that is the same as gold at 77 K (0.1 Ω) and having a R_s of 1Ω in the normal state. It has an exceptionally narrow insertion loss envelope and excellent return loss.

Bolometric switches have an "on" resistance of nearly 0 Ω and an "off" resistance of 0.1-4 kΩ. In microwave application, their kinetic inductance and skin resistance must also be taken into account in calculating their "on" impedance. These switches are approximately 25μm x 1000μm. Their speeds, however, are very low-around 1s. They can be redesigned, however, to be as fast as 10μs [12]

We have fabricated the above phase shifter and we now discuss the bolometric response of one of its switches. Figure 3 shows the resistance versus temperature curve of this switch. The transition width is somewhat large-about 1 K. This is mainly due to the very narrow channel. Figure 3 also shows the bolometric response of this switch. We will report the microwave characteristics of this phase shifter in the future.

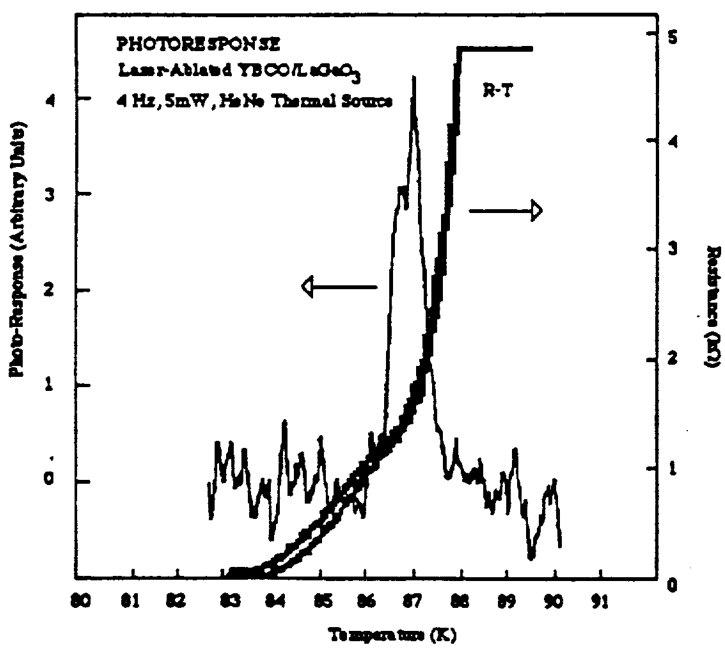


Figure 3 Resistance versus temperature graph (solid line) and the bolometic response of a superconducting switch. To obtain the bolometric response, the device was illuminated with a 5mW HeNe laser that was chopped at 4 Hz. The channel width was 10 μm and the channel length was 0.5 mm.

A typical fabrication sequence starts with the growth of the HTS film, followed by its patterning, etching, and metallization. Growth of the $YBa_2Cu_3O_{7-x}$ films on microwave substrates is discussed in references 23-26. Patterning is discussed comprehensively in reference 25.

Bolometric devices are quite easy to fabricate. After the film is grown, it is patterned and the bolometer is defined. Then the devices are annealed in an oxygen rich environment to increase the oxygen content in the film and to compensate for any losses that might have occured in the previous stages. In reference 25 we discussed the side effects of the patterning of HTS $YBa_2Cu_3O_{7-x}$ films comprehensively. We concluded that patterning lowers the T_c of the film by only a fraction of a degree-for all practical purposes, negligible. A more significant problem is the potential non-uniformity of T_c over the film. In the case of the bolometric devices, where all the devices are thermally biased near their transition temperature, a spatial non-uniformity in T_c is not acceptable and local control over the bias temperature may be required. The degree of the spatial non-uniformity of T_c depends on the growth technique. In laser ablated-films, non-uniformity of T_c is only fraction of a degree over a 1 cm^2 wafer.

As growth techniques mature, highly uniform films will become a reality and the scatter of T_c of these devices may soon be within 1/10 of a degree for a 1 cm^2 microwave circuit. Meanwhile, we may solve this problem by locally tailoring the T_c of a device by laser heating, which causes a preferential oxygen loss in the HTS film of the device and therefore lowers its T_c. This technique can be used to lower the T_c of all the devices on a wafer accurately to 77 K so that rather inexpensive liquid nitrogen can be used directly without a temperature control unit.

Photonic Devices. Non-equilibrium optical excitation can be used to switch the state of a superconductor to normal conductivity [13]. In the case of ceramic superconductors, the coupling cross section between the photons and charge carriers is not known yet. It is not clear whether this cross section is large enough to allow the useful employment of this excitation process in superconducting switches. The speed of such a device, however, will surpass all other devices discussed here.

Magnetic Field Effect Devices. In these devices, an inductive loop generates a magnetic field parallel to the a-b plane of a $YBa_2Cu_3O_{7-x}$ film as shown in Figure 4. $YBa_2Cu_3O_{7-x}$ is a type II superconductor and vortices can be easily generated in it by relatively low magnetic fields [14]. A vortex containing a quantum of magnetic flux in the presence of a current leads to dissipation of energy in the film, so vortices can be generated to effectively increase the resistivity of the film or to destroy its superconductivity.

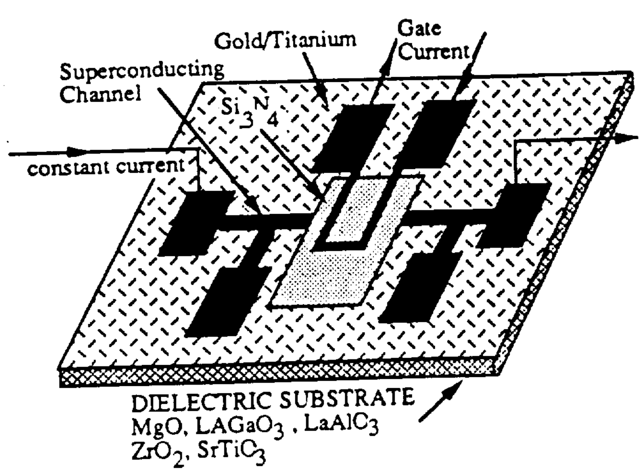
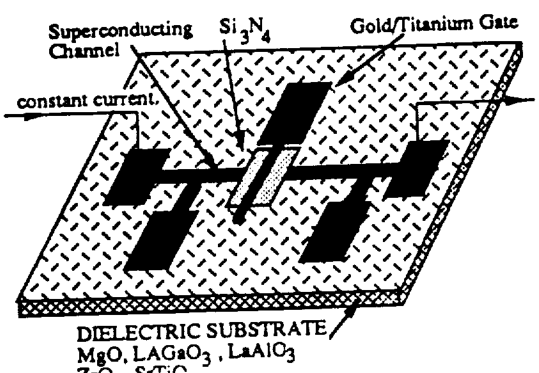


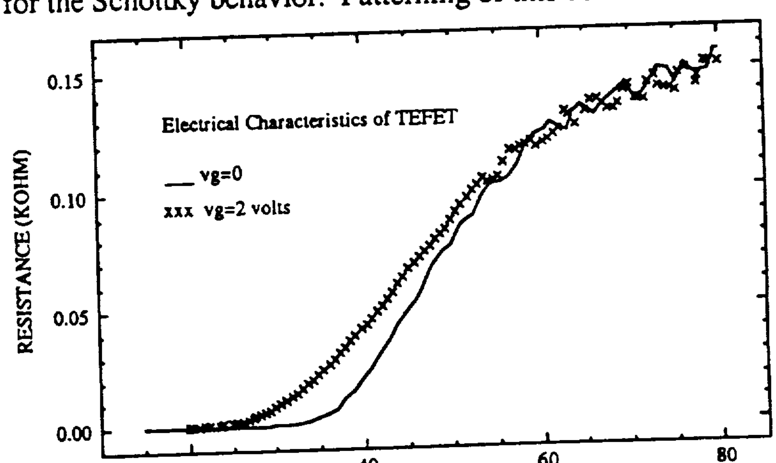
Figure 4 Schematic of a magnetically controlled superconducting switch.

Transverse Electric Field Effect Devices. These devices operate on a principle very similar to that of FET devices, where the electric field effect controls the conductivity of the channel. Because T_c is a function of the carrier density in superconductors[15-22], we propose to control T_c by electrostatically controlling the surface charge density of a superconducting channel [21]. The feasibility of this idea has already been demonstrated in normal superconductors [15-17]. In normal superconductors, T_c is a weak function of the electric field. However, in ceramic superconductors T_c can be made to be a strong function of an applied electric field because the normal carrier densities in these materials are an order of magnitude less than in metallic superconductors. Moreover, carrier density in ceramics can be tailored by doping [22].

Figure 5a shows a superconducting electric field-effect device [21]. This structure consists of a thin channel a few thousand Å thick and 5-50μm wide, consisting of the superconducting material with two pads at each end to allow four point resistance measurements. Ohmic contacts were made directly to the superconductor by attaching 2 mil gold wires with a wedge wire bonder. A Schottky contact was made to the superconductor structure midway along the channel by depositing on the sample 10nm of titanium followed by 200nm of gold by evaporation. It is believed that interaction of titanium with the oxygen in the superconducting material is responsible for the Schottky behavior. Patterning of this contact was done by the lift-off technique.



(a)



(b)

Figure 5 a) Schematic of an electric field-effect superconducting transistor. b) The resistance versus temperature characteristics of the electric field-effect transistor with two different gate biases of 0 and 2 volts. The channel current was 0.5 mA. The channel width was 10 μm and its thickness was 2000 Å. The gate width was 10 μm.

The AC resistance of the channel at 1kHz was measured as a function of temperature while different DC voltages were applied across the Schottky contact and the ground pads (see Figure 5b). As Figure 5b shows, the transition temperature of the channel can be lowered considerably by this voltage. For this device, the influence on the transition temperature is due to the critical current being exceeded by the applied gate voltage. We are now refining our fabrication procedure to take advantage of weak links between the superconducting grains and to modulate the current by modifying the intergranular barrier heights using the electric field effect. This device can switch between a zero resistance and several hundred Ohms if it is maintained just below the transition temperature at T_S (Figure 5b).

Field-effect switches have an "on" resistance of 0 Ω and an "off" resistance of 0.1-4 kΩ. In microwave application, their kinetic inductance and skin resistance must also be taken into account in calculating their "on" impedance. These switches are about 50μm x 1000μm, and they can easily be scaled down to the size of a typical semiconductor FET.

Fabrication of the active field-effect superconducting device is slightly more involved than that of a bolometric device, because it requires an insulating layer between its channel and gate. However, the lift-off technique has been conveniently used to define the insulating layer, as discussed in reference 21. Since the gate voltage or current (in the case of magnetic field effect devices) can be used to change the channel resistance, the requirement of spatial uniformity of T_c is not as stringent for field-effect devices as it is for the bolometric devices.

__Longitudinal Electric Field Effect Devices__. A pseudo-three-terminal switch is shown in Figure 6. In this device, exceeding the critical current density between the gate and the source turns off the superconducting drain-to-source channel. This device offers very poor input-to-output isolation (almost zero) and excellent off-to-on resistance ratio (almost infinity). It is also extremely easy to fabricate and does not require a heat or light source. Current sources have large impedances; for this device to work, the impedance of the switch in both the "on" and "off" states must be smaller than that of the biasing circuit at microwave frequencies.

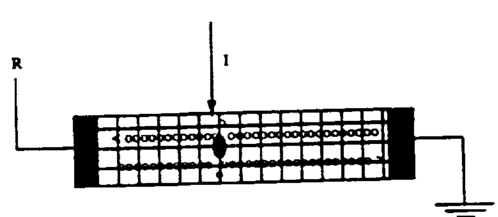


Figure 6 Schematic of a longitudinal electric field-effect device.

IV. DISCUSSION & CONCLUSION

To compare the performance of the above devices, we show their pertinent parameters in Table I. In this table "speed" is the inherent switching speed of the corresponding device. The off-to-on resistance ratio is denoted by "R_{off}/R_{on}" and is measured at dc. For bolometric devices, R_{off}/R_{on} is not infinite because these devices are thermally biased slightly above their zero-resistance state for maximum responsivity. The capacitance in the off state is denoted by "C_{off}" and is measured at 1MHz. A more relevant parameter in analysing the superconducting microwave switch is its kinetic inductance and skin resistance. We have not considered these here. High-frequency considerations will only result in somewhat lower off-to-on impedance ratios. The power needed to turn on a device is denoted by "P." This power is only an estimate and, therefore, it is discussed qualitatively. The isolation between the input (control signal) and the output (microwave) is denoted by "in/out isolation." For bolometric and photonic devices, the input-output isolation is very large, almost infinite. Size is denoted qualitatively, taking into account the entire circuit. The complexity of the switching circuit and its fabrication are also described qualitatively, lightly taking into account the fabrication steps and issues. Table I shows that the bolometric switches are very easy to fabricate and that they offer excellent input-to-output isolation as well as a good off-to-on resistance ratio. Their only drawback is their speed. Non-bolometric superconducting switches, on the other hand, are very fast.

TABLE I

Device	Speed (ns)	R_{off}/R_{on}	C_{off} (pF)	Power	in/out isol.	Size	Circuit /Fabric.
PIN	200	4×10^6	0.4	high	small	med.	high
MESFET	<1	8×10^4	0.4	med	small	small	med.
MISFET	<1	10^5	0.2	low	large	small	med.
Bolometric	10^4	$> 10^7$	< 0.1	high	∞	med.	low
Photonic	10^{-3}	∞	< 0.1	low	∞	med.	high
LEFET#	0.1	∞	< 0.1	med.	low	med.	med.
TEFET$	1	$>10^7$	0.4	low	high	med.	med.

\# Longitudinal Electric Field-Effect Transistor.

$ Transverse Electric Field-Effect Transistor.

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16. Abstract

This paper compares the performance of semiconductor and high-T_c superconductor switches as they are used in delay-line-type microwave and millimeter-wave phase shifters. We compare such factors as their ratios of the off-to-on resistances, parasitic reactances, power consumption, speed, input-to-input isolation, ease of fabrication, and physical dimensions. Owing to their almost infinite off-to-on resistance ratio and excellent input-to-output isolation, bolometric superconducting switches appear to be quite suitable for use in microwave phase shifters; their only drawbacks are their speed and size. We also discuss the SUPERFET, a novel device whose operation is based on the electric field effect in high-T_c ceramic superconductors. Preliminary results indicate that the SUPERFET is fast and that it can be scaled; therefore, it can be fabricated with dimensions comparable to semiconductor field-effect transistors.

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