A Hybrid Phase Shifter Circuit Based on TlCaBaCuO Superconducting Thin Films

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Abstract—**A superconductor–semiconductor hybrid reflection-type phase shifter circuit has been designed, fabricated, and characterized for 180° phase bit with center frequency of 4 GHz and bandwidth of 0.5 GHz for operation at 77 K. All of the passive components of the phase shifter circuit such as input/output feed lines, 3 dB Lange coupler, impedence matching networks, and transmission lines consisted of thallium based superconducting TlCaBaCuO thin films of 4000 Å thickness on lanthanum aluminate substrate. Metal-Schottky field-effect-transistors (MESFET's) on GaAs semiconductor were used as active devices for switching action (on-state and off-state) in the phase shifter circuit. The phase shift and insertion losses were investigated as a function of frequency from 3.6 to 4.6 GHz at 77 K. The circuit exhibited a fairly flat response of 180° phase shift with a maximum deviation of less than 2° and a maximum insertion loss of 2 dB for on-state and 2.2 dB for off-state conditions over 0.5 GHz bandwidth at 4 GHz. The insertion losses were also fairly flat within the bandwidth. The insertion losses were constant between 50 and 80 K, giving the circuit a large range of operation at or below 77 K. The performance of this circuit as compared to a gold microstrip-semiconductor circuit designed identically was superior by a factor of 1.5, and may be due to lower conductor losses and lower surface resistance in the superconducting microstrips.**

I. Introduction

The foremost applications of high T_c thin films are expected to be in the area of "passive microwave devices" such as resonators, filters, delay lines, and other passive microwave structures [1]–[3]. High T_c superconductors (HTS) have a greater impact on selected microwave devices because of two important properties that differ from normal metals at high frequencies. One is the lower surface resistance in HTS thin films compared to Cu and Au, corresponding to higher Q and improved performance in passive microwave devices. The second advantage is the frequency independent penetration depth as compared to frequency dependent skin depth in normal conductors. This means that dispersion introduced in superconducting components will be negligible up to frequencies as high as hundreds of gigahertz. Because of lower losses in superconductors, reduction in size is another advantage using the HTS thin films. Compact delay lines, chirp filters, and resonators are possible [2], [3]. The lower conductor losses in the HTS microstrips would give lower insertion loss and superior performance of phase shifters.

Manuscript received March 16, 1994, revised July 11, 1994. This work was supported by the NASA Lewis Research Center.

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IEEE Log Number 9407442.

Phase shifters are essential components for electronic steering of phased array antennas in communications systems [4]. The function of a phase shifter is steady control of relative phase between input and output. The phase of each antenna element is controlled such that a radiated beam of any desired shape can be formed. Superconducting phase shifters have been investigated by several researchers, including the use of HTS and semiconductor based hybrid circuits [5]–[7]. YBCO films together with PIN diodes [5] were used to investigate a 4-bit superconducting phase shifter with the insertion loss of 4–5 dB over 10% bandwidth at 10 GHz. However, the simulation results indicated a maximum total insertion loss to be 1.1 dB at 10 GHz, and about 1.5–2.0 dB less than that of a copper phase shifter. An YBCO HTS monolithic phase shifter using 40 integrated SQUID devices has been reported [6] with a phase shift of 10–20° at 77K and a phase shift of greater than 60° below 65 K. Niobium transmission line coupled to Nb based SQUID's [6] has been investigated for 60° phase shift at 10 GHz. However, no work has been reported on the use of superconducting TlCaBaCuO thin films on lanthanum aluminate ($LaAlO_3$) substrate in combination with GaAs active devices to investigate circuits to obtain a flat phase shift response within the desired bandwidth and minimum insertion loss compared to normal metal-based phase shifters. Among the high T_c materials, the TlCaBaCuO compound has proven to possess the highest T_c [8], [9] as well as superior microwave performance [10], which means a wide margin of operational range is available for microwave electronic applications at 77 K.

This paper describes the design, fabrication, characterization, and simulation of a reflection-type hybrid superconductor–semiconductor phase shifter circuit to obtain a minimum insertion loss and a fairly flat response of 180° phase shift over the 0.5 GHz bandwidth at 4 GHz for operation at 77 K. All of the passive components including the 3 dB Lange coupler of the phase shifter circuit consisted of high temperature superconducting TlCaBaCuO microstrips on $LaAlO_3$ substrate, and the active devices were high-frequency GaAs MESFET switches. The phase shift and the insertion losses were investigated as functions of frequency and temperature. The measured results were compared to the simulation result as well as with a gold microstrip-semiconductor phase shift circuit designed for the same parameters. This paper describes the results of these investigations.

II. Design

The digital phase shifters can be realized using three different configurations: loaded line phase shifters, reflection-type phase shifters, and switched line phase shifters. Among the three, the reflection-type phase shifters are more suitable for large phase bits, due to their low insertion loss, wide bandwidth, and the use of only two switching field-effect transistors (FET's) per bit. A reflection-type hybrid superconductor–semiconductor phase shifter was designed for 180° phase shift, at 4 GHz with phase error less than 2° over the 0.5 GHz bandwidth, and phase error of less than 5° over the 1 GHz bandwidth. In addition, the circuit was designed to have an insertion loss less than 2 dB, for reciprocal operation, and for the operating temperature of 77 K. The hybrid digital phase shifter circuit consisted of a 3 dB Lange coupler, impedance matching network, and active switch transistors shown as a block diagram in Fig. 1. The superconducting microstrip circuit consists of input and output feed lines, interdigitated 3 dB Lange coupler which divides the input power (e.g., 1 mW or 0 dBm) equally between the coupled and direct ports (0.5 mW/-3 dB) of the Lange coupler, and impedance transforming network for matching the impedance of the switching transistors which act as the reflection plane to the Lange coupler. The Lange coupler is a special microstrip 3 dB coupler which provides octave bandwidth. The device consists of interdigitated coupling section which compensates for the odd and even mode phase velocity dispersion over a wide frequency range [11]. If the width of the interdigitated fingers and the spacing between the fingers is designed carefully, the input signal power can be divided equally between the direct and coupled ports, with minimum insertion loss. The design of the coupler was performed carefully, keeping the coupler loss below 0.3 dB in the frequency range between 3.5 and 4.5 GHz. An interdigitated coupler can be easily realized in the microstrip form [11]. The impedance matching network (A) was designed using transmission lines and open circuit stubs. GaAs MESFET active devices were used for switching applications in the hybrid circuit. By suitable design of the 3 dB Lange coupler, impedance transforming network, and proper terminations in the direct and coupled ports, any desired phase angle can be obtained. The desired phase shift may be obtained by changing the switching states (on-state, off-state conditions) of the switching transistors.

The first step in the design of the phase shifter was to investigate the scattering parameters for the switching transistors to determine their insertion losses and isolations. From these results, an equivalent circuit approximation was determined to facilitate the design of impedance matching networks and subsequently the entire phase shifter circuit.

The GaAs MESFET's can be used for switching applications at the lower end of the microwave frequencies due to their low insertion loss, single power supply requirements, and high switching speed [12]. A GEC Marconi general-purpose amplifier GaAs depletion mode MESFET (P35-110) was chosen for switching, which has a high transconductance (g_m) of 45 mS, a low gate leakage current of 10 nA at −5 V, a low gate-source capacitance (Cgs) of 0.4 pF, and large pads for ease of bonding. The width of the device was 2×150 μm. The positive or zero gate bias (V_c) was applied to MESFET's through a thick film 5.1 kΩ resistor to obtain the low impedance state (on-state condition) and negative gate

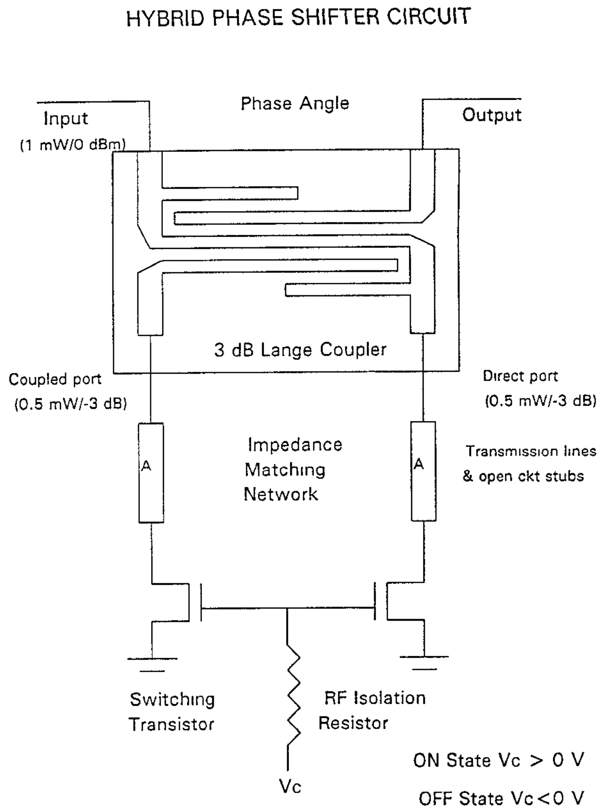

Fig. 1. Schematic representation of a hybrid superconductor–semiconductor phase shifter circuit with input/output feed lines, 3 dB Lange coupler, impedance matching network transmission lines, and MESFET switching transistors on GaAs semiconductor.

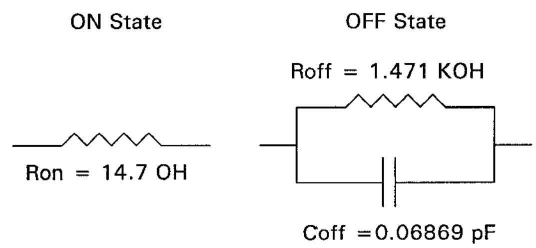

Fig. 2. The equivalent circuit representation of the MESFET in the on-state and off-state conditions of the devices.

bias was applied to obtain the high impedance state (off-state condition) of the transistors [12]. This resistor also provided isolation from the RF path. The transistors were packaged in a special chip carrier and a standard two port through-reflect-line (TRL) calibration was performed between 2.5 and 5.5 GHz [13].

The results of the scattering parameters of the GaAs MESFET's yielded the insertion loss (S_{21}) to be constant at approximately 1.3 dB, and isolation was approximately 18–15 dB for the 3.6–4.2 GHz frequency band measurements. From these measurements, the equivalent circuits for the on and off states of the MESFET were extracted following a simplified model [14]. The on-state impedance was assumed to be purely resistive (R_{on} = 14.7 Ω) and the off-state impedance was modeled by a parallel R (R_{off} = 1.471 kΩ) and C (C_{off} = 0.068 pf) combination. The equivalent circuit obtained for both states at cryogenic temperatures is shown in Fig. 2.

For the design and modeling of the passive components of the phase shifter circuit using TlCaBaCuO, the kinetic inductance effect of HTS thin films should be included when the penetration depth is on the order of film thickness [10]. Several models have been reported which are based on the calculation of internal impedance using complex conductivity approximation for the superconductor [15]–[17]. The superconducting microstrips for the passive components were designed based on the characteristic impedance changes due to the kinetic inductance. By knowing the superconducting properties of the films, the kinetic inductance and hence the wave slowing factor were calculated [17]. An effective characteristic impedance was determined so that when the sample is superconducting, the impedance of the microstrip would be the desired characteristic impedance. The lossy superconductor can be treated as a normal conductor with complex conductivity, as in the PEM model [15]. In this model, the distributed internal impedance of the superconductor is obtained from an equivalent single strip model for the planar quasi-TEM line. The attenuation coefficient can be obtained from the approximation $R_i/(2Z)$, where R_i is the real part of internal impedance, and Z is the characteristic impedance of the microstrip line. The propagation constant of the microstrip line can be obtained from the approximation $X_i/(2Z)$, where X_i is the imaginary part of the internal impedance. From the distributed internal impedance, the propagation characteristics of the superconducting transmission line can be obtained. The following procedure was followed. The internal inductance (L_i) of the superconducting microstrip, based on the PEM model, was calculated; then the effective wave slowing factor (n) from the additional inductance introduced due to the field penetration [16] was determined; and then the effective characteristic impedance (Z_e) of the microstrip following the model proposed by Antsos [17] was calculated. This was followed by the design of the microstrip for this effective characteristic impedance, so that the impedances of the normal and superconducting microstrips will be the same at a particular temperature.

The effective calculated characteristic impedance (Z_e) versus penetration depth characteristics is shown in Fig. 3, with the superconducting microstrip thickness as a parameter at 77 K. The effective characteristic impedance differs from the desired 50 Ω characteristic impedance by a large percentage at higher penetration depths and at smaller thicknesses of the microstrip.

The final design of the phase shifter circuit was performed using Hewlett Packard Microwave Development Software (HPMDS) on a SUN workstation using the measured scattering parameters of the GaAs MESFET switch transistors and the modeled effective characteristics impedance of the HTS microstrips as discussed above [18]. The optimum design layout of a digital phase shifter circuit for 180° phase shift at 4 GHz center frequency with a bandwidth of 0.5 GHz for 20-mil-thick $LaAlO_3$ substrate at 77 K is shown in Fig. 4. The optimization process for the on- and off-state conditions of the switch transistors was performed simultaneously so as to obtain the optimum design. The width (W) of all the superconducting microstrips throughout the phase shifter circuit was optimized to be 6.88 mil for 50 Ω characteristic impedance taking into account the effect of kinetic inductance at 77 K. The main reason to fix the characteristics impedance to 50 Ω was to improve the validity of the comparison of gold microstrip and superconducting microstrip circuits for the same characteristic impedance. The 3 dB Lange coupler consisted of six interdigitated fingers of 193.1 mil length with finger width (Wf) being 22.5 μm and the spacing (S) between the fingers was 34.1 μm. The impedance transforming network was designed using transmission lines and open circuited stubs to match the impedance of the switching transistors to the Lange coupler. The optimization variables were the lengths of the open circuit stubs ($L2$ = 39.6 ml and $L4$ = 51.89 mil), length of input and output feedlines ($L1$ = 107.3 mil), and the transmission lines ($L3$ = 193.23 mil) of the midsection of the matching network. The GaAs MESFET switch transistors were bonded to the impedance matching network to obtain the hybrid superconductor–semiconductor phase shifter circuit as shown in Fig. 4. The size of the phase shifter circuit chip fitted in 1 cm×1 cm substrate. A similar gold microstrip-semiconductor phase shifter circuit designed for 50 Ω characteristic impedance, with 6.8 mil width, was also fabricated for comparison purposes.

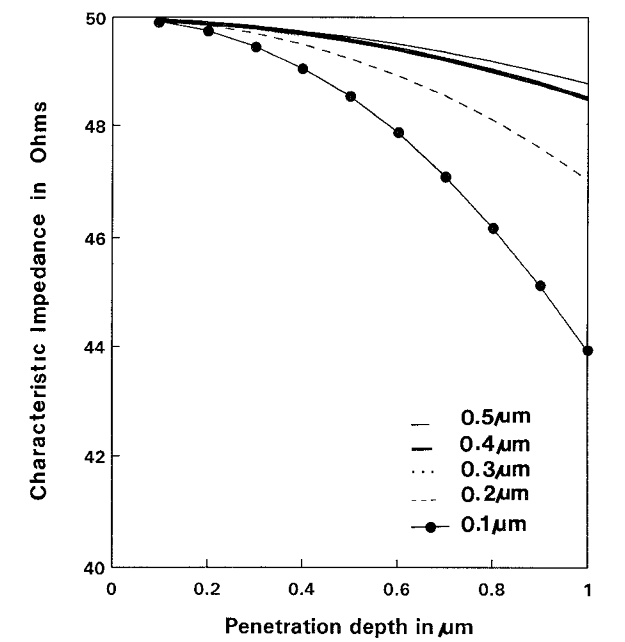

Fig. 3. The modeled effective characteristic impedance of the thallium-based superconducting microstrip versus penetration depth for various microstrip thicknesses.

III. Fabrication and Testing

$Tl_2Ca_1Ba_2Cu_2O_x$ (2122) superconducting thin films were fabricated by RF magnetron sputtering from a sintered Tl_{2122} powder target in a pure argon plasma, and postannealing methods. The details of the reproducible deposition process for the TlCaBaCuO high temperature superconducting (HTS) thin films on 2-in-diameter (100) $LaAlO_3$ substrates with superior microwave properties have been reported in [10] and [19].

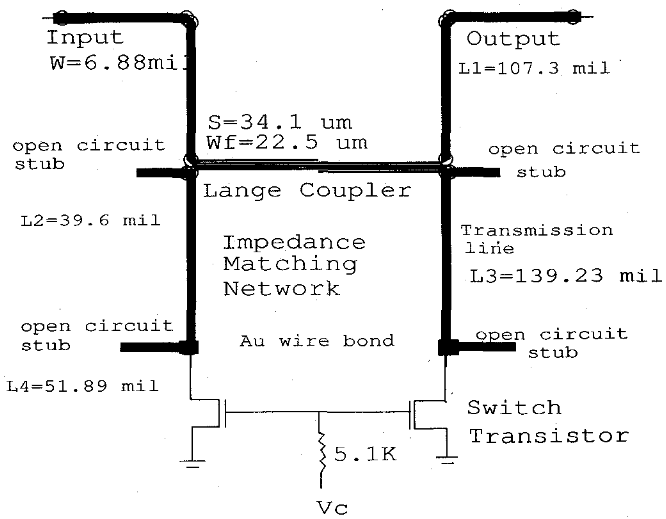

Fig. 4. Schematic representation of the design and layout of the hybrid phase shifter circuits where the width of the microstrip (W) is constant at 6.88 mil throughout the circuit. $S, Wf, L1, L2, L3$, and $L4$ are defined in the text.

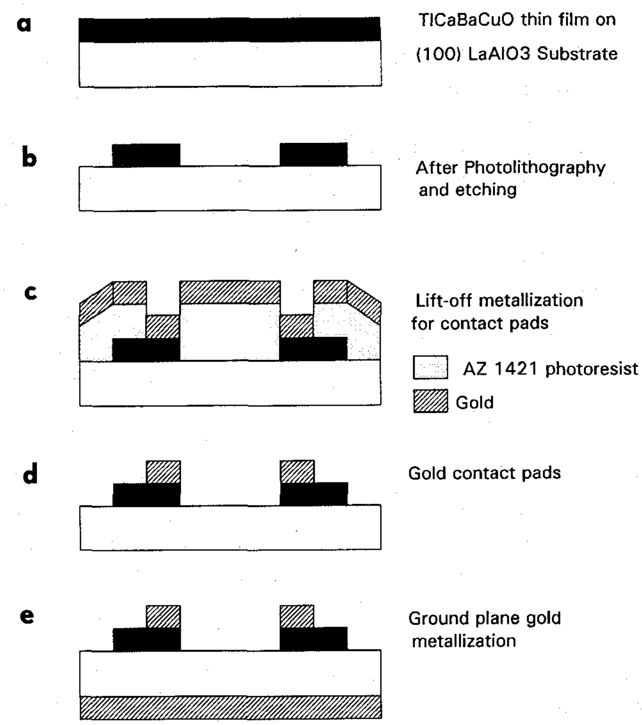

Fig. 5. Fabrication process cross section for TlCaBaCuO superconducting microstrip on $LaAlO_3$ substrate for passive components of the phase shifter circuit.

The cross section of the HTS microstrip based phase shifter circuit fabrication process is shown in Fig. 5. The double side polished 2 in (100) $LaAlO_3$ substrates were degreased in acetone, methanol, rinsed in deionized water, and blown dry using nitrogen. After the initial cleaning, TlCaBaCuO thin films of approximately 4000 Å were deposited on the substrate at an RF power density of 0.7 W/cm^2, and the chamber pressure at 5 mTorr, in a pure argon atmosphere [Fig. 5(a)]. The sputter-deposited thin films were then sintered in air in an optimum Tl partial pressure at 850°C for 10 min. The sintered TlCaBaCuO thin films were patterned into the phase shifter circuit using AZ1421 positive photoresist photolithography and wet chemical etching techniques. The films were coated with an HMDS adhesion layer followed by spinning a 1-μm-thick AZ-1421 photoresist layer. The samples were softbaked at 90°C for 20 min. Then the samples were exposed to UV light through a contact mask for approximately 4.5 s in the Karl Suss mask aligner. The photoresist was developed in a 1 : 5 AZ developer : DI water solution for 1 min. After the development, the samples were hard baked at 85°C for 15 min. After the photolithography, the films were etched in a 1 : 100 phosphoric acid : +DI H_2O solution heated to 75°C. The etch rate in this solution was approximately 40 Å/min. The photoresist was removed by acetone soak to complete the patterning process [Fig. 5(b)]. The samples were then annealed in oxygen at 750°C for 15 min to improve the oxygen content and remove any degradational layers formed due to the etching process [9], [10].

An additional photolithography step was needed for lift-off metallization for gold contact pads to the HTS films in the phase shifter circuit. AZ 1421 positive photoresist lift-off technique was used for the contact pad definition. A chlorobenzene soak for approximately 2.5 min was needed to define the lip structure that is required for lift-off lithography. 4000 Å of gold was evaporated thermally [Fig. 5(c)]. The samples were soaked in acetone for lift-off. After lift-off, the contact pads of 4000 Å were annealed at 450°C for 10 min in a flowing oxygen (1 l/min), and then rapidly cooled [Fig. 5(d)]. This step reduces the contact resistance between the HTS thin film and the gold contacts [10]. The ground plane gold was evaporated to a thickness of approximately 2 μm to form the phase shifter circuit [Fig. 5(e)]. Gold wires of 1 mil diameter were bonded using a Kulicke and Soffa Model 4123 utlrasonic wedge bonder between the gold pads and the GaAs MESFET chips and the thick film 5.1 kΩ gate isolation resistor. The bonding process did not require sample heating.

A gold-semiconductor phase shifter circuit designed for identical design parameters using gold microstrips of 3 μM thickness was fabricated to compare the results to high temperature superconducting microstrip phase shifter. The identical GaAs switching transistors were also used for the gold-semiconductor circuit.

The complete phase shifter circuit, including switching transistors, was mounted in a gold-plated copper test fixture 1 cm wide, 1 in long, and 1/2 in thick. The test fixture was placed on the cold head of the helium gas closed-cycle cryogenic system [10]. Electrical connection to the feed line was obtained by mechanical contact of a launcher at the input side of the test fixture. Connections to the HP 8720 network analyzer were made using a 0.141 in semirigid coaxial cable of 50 Ω characteristic impedance [13]. A TRL two-port calibration was performed prior to the circuit measurements. The calibration was performed using an open, a short, and a through to effectively remove the test system imperfections introduced by the interconnecting cables, adapters, etc. [13]. The calibration was assumed valid at lower temperatures.

IV. RESULTS

The results of the measurements indicated that the Tl-CaBaCuO thin films after patterning and etching had very reproducible properties [9], [10], [19] over the entire 2 in $LaAlO_3$ wafer. The temperature dependence of resistance of the films showed the onset of critical transition temperature at 114 K, and zero resistance at 103 K. Scanning electron microscopy and X-ray diffraction results showed the smooth and highly c-axis oriented nature of the thin film with the predominantly 2122 phase. The specific contact resistivity for gold contacts ranged from 3.65×10^{-5} Ω cm^2 at 90 K to 2.3×10^{-11} Ω cm^2 at 77 K, and 10^{-10} Ω cm^2 below 77 K. Current densities at zero magnetic field as high as 5×10^5 A/cm^2 at 77 K and 1×10^6 A/cm^2 at 60 K were obtained. The surface resistance of the HTS film was as low as 1.5 mΩ at 77 K at 12 GHz, almost an order lower than CU and AU at the same temperature and frequency [10]. The effective penetration depth at 0 K was determined to be between 7000 Å and 8000 Å.

The phase shift versus frequency characteristics from 3.6 to 4.6 GHz for three different phase shifter circuits at 77 K is shown in Fig. 6. The 0.5 GHz bandwidth between 3.75 and 4.25 GHz is shown by dotted lines with a center frequency of 4 GHz. The curve A represented by a solid line is for the simulated (theoretical) characteristics which was simulated using HPMDS software described in the design section. It can be seen that the simulated circuit has flat response of 180° phase shift within the 0.5 GHz bandwidth at a center frequency of 4 GHz. The maximum deviation of the phase shift from the nominal value was approximately 4° at 3.6 GHz and 3° at 4.6 GHz. The curve B with open circles is the measured characteristics for the superconductor–semiconductor phase shifter circuit. It had a flat phase shift response with a maximum deviation of less than 1.5° from the nominal value of 180° phase shift within the 0.5 GHz bandwidth. The deviation of the phase shift was less than 5° at 3.6 GHz and 3° at 4.6 GHz. The circuit exhibited superior microwave performance as the maximum total deviation of the phase shift was less than 1.5° and 8° over the 0.5 GHz and 1 GHz bandwidths, respectively, for the 4 GHz center frequency. This exceeded the design requirements of the superconductor–semiconductor phase shifter circuit. Curve C with solid circles is the measured data for the gold (AU) semiconductor phase shifter circuit with a 180° phase shift at the center frequency of 4 GHz. This circuit had a maximum total deviation of 14° and 25° over the 0.5 GHz (3.75–4.25 GHz) and 1 GHz (3.6–4.6) bandwidth, respectively. The measured phase shift versus frequency for both the gold and HTS phase shifter circuits exhibited a sharp drop-off from 180° above 4.25 GHz. The possible reason for the divergence from the simulated (theoretical) curve is the frequency dependent parasitics introduced in the measurements through bonding pads, bond wires, contacts, and at the input and output feedlines.

The insertion loss of the phase shifter circuit versus frequency characteristics from 3.6 to 4.6 GHz during the on-state and off-state conditions at 77 K is shown in Fig. 7. The bottom and top diagrams are for the on-state and off-state conditions of the circuits, respectively. The insertion loss is the magnitude of "S_{21}" in decibels. The curves A represented by a solid line are for theoretical plots which were simulated using HPMDS software and input data file of the measured frequency dependent insertion losses of the MESFET switching transistors. The simulated circuits have essentially flat response with a −1.7 dB insertion loss for the on-state and −2.0 dB for the off-state as shown by curves A of Fig. 7. The major portion of these insertion losses may be due to the insertion loss of approximately 1.3 dB of the MESFET's switching transistors as discussed in the design section. The curves B with open circles are the measured characteristics for the superconductor–semiconductor phase shifter circuit. The insertion loss is fairly flat (2.0 dB for on-state, 2.2 dB for off-state) over 0.5 GHz bandwidth. The insertion losses for the two states in this bandwidth are essentially equal within the measurements error. This would result in a stable radiation pattern if the phase shifter is to be used in an antenna array [5]. The curves C in Fig. 7 with solid circles are the measured data for the gold microstrip-semiconductor phase shifter circuit. The minimum insertion losses in the gold circuits were approximately 5.1 and 6.2 dB at 4 GHz center frequency for the on-state and off-state, respectively. These losses increased sharply within the 0.5 GHz bandwidth. The steep falling of the losses may be due to frequency dependent additional parasitics in the circuit as well as enhancement of loss due to the radiation, and interface mismatch of the $LaAlO_3$ substrate with the gold conductor. The modeling of the gold based hybrid phase shifter circuit showed a phase error less than 10° in the frequency range of 3.5–4.5 GHz. The minimum insertion losses in the off-state and on-state of the switching devices were 1.74 and 3.16 dB, respectively. The overall superior performance of the superconductor–semiconductor phase shifter circuit as compared to the gold-semiconductor circuit may be mainly

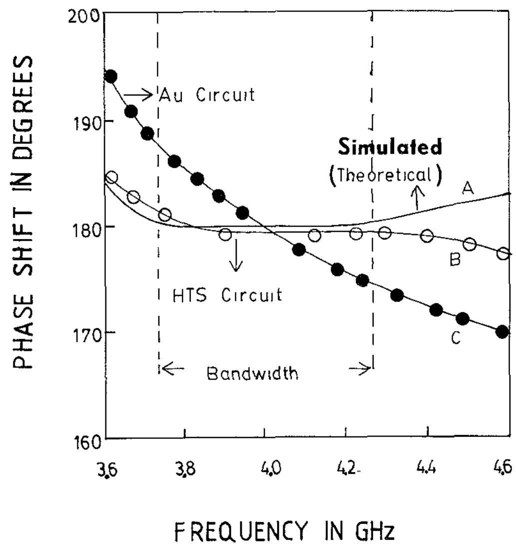

Fig. 6. The phase shift versus frequency characteristics for the hybrid phase shifter circuit at 77 K. The simulated (theoretical) result is shown by solid line curve A, the measured data for the superconductor–semiconductor circuit is given by curve B with open circles, and the measured data for fold (AU) microstrip-semiconductor circuit is given by curve C with solid circles.

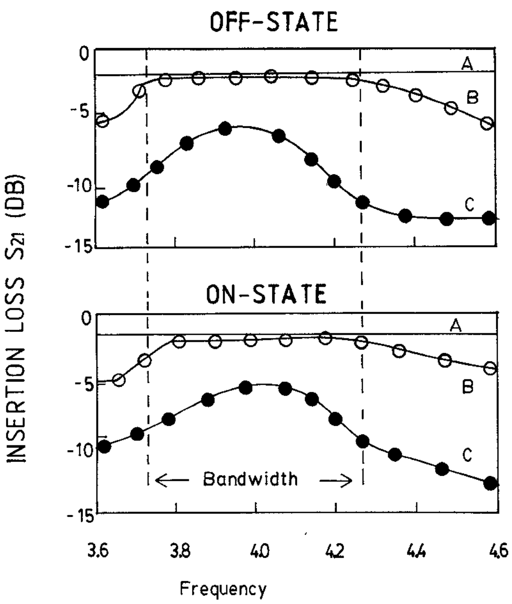

Fig. 7. Insertion loss versus frequency characteristics for the phase shifter circuit for the on-state (lower curves) and for the off-state (upper curves) at 77 K. The theoretical simulated results are shown by solid line curve A, the data for superconductor-semiconductor circuit is indicated by curve B with open circles, and data for gold-semiconductor is given by curve C with solid curves.

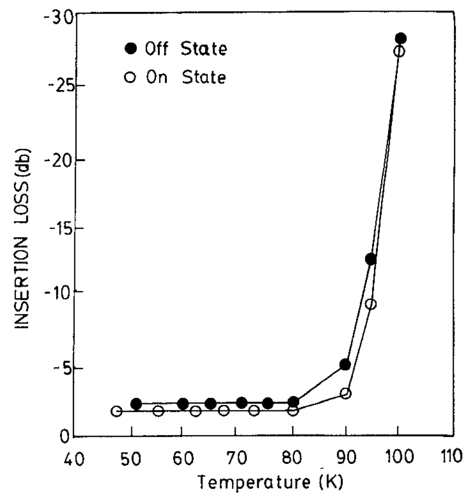

Fig. 8. The measured temperature dependence of the insertion loss of superconductor-semiconductor phase shifter circuits for on-state (curve with open circles) and for off-state (curve with solid circles) at 4 GHz.

due to lower conductor losses and lower surface resistance in the superconducting microstrips.

The measured output reflected power (S_{22}) for the superconductor–semiconductor phase shifter was -23.1 and -16.35 dB for the on and off states, respectively, resulting in effective output impedance matching.

Fig. 8 shows a typical measured insertion loss versus temperature data at 4 GHz for superconductor–semiconductor phase shifter circuit for the on-state and off-state conditions. The characteristics show a sharp decrease in insertion loss below 100 K, the onset of T_c of the TlCaBaCuO microstrip. The insertion loss does not change appreciably below 80 K. The variation of the insertion loss above 80 K may be due to large temperature dependence of superconducting properties of the microstrip such as surface resistance near T_c, whereas the surface resistance does not change very much between 50 K and 80 K [10].

V. Summary

A hybrid superconductor–semiconductor phase shifter circuit was investigated for 180° phase shift at 4 GHz over the 0.5 GHz bandwidth for operation at 77 K. All of the passive components of the circuit including input/output feedlines matching network, 3 dB Lange coupler, were made of TlCaBaCuO superconducting thin film microstrips of 4000 Å thickness on 20-mil-thick $LaAlO_3$ substrate.

The phase shift and insertion losses of the superconductor–semiconductor phase shifter circuits were investigated as a function of frequency from 3.6 to 4.6 GHz at 77 K. The superconductor–semiconductor circuit exhibited a fairly flat response of phase shift with a maximum deviation of less than 2° from the nominal value of 180° phase shift within the 0.5 GHz bandwidth (3.75–4.25 GHz), and less than 8° over the 1 GHz bandwidth (3.6–4.5 GHz). These results compare very well to the simulated results for the superconductor–semiconductor phase shifter. The insertion loss for the superconductor–semiconductor phase shifter was fairly flat at 2 dB for on-state and 2.2 for off-state within the 0.5 GHz bandwidth (3.75–4.25) at 77 K. This would be ideal for low power phase array antenna applications as it would result in a stable radiation pattern.

The phase shifter's insertion losses of approximately 2 dB may consist of two major parts—one from the passive components and the other from the measured loss of the GaAs MESFET's. Therefore, the entire circuit had inherent "built-in" 1.3 dB insertion loss due to MESFET's and approximately 0.7 dB insertion loss which may be from the rest of the circuit including all superconducting components.

A gold-semiconductor phase shifter circuit was also designed, fabricated, and characterized in which all of the passive components consisted of gold microstrips with similar design parameters. The active devices were also identical GaAs MESFET's. The gold microstrip-semiconductor circuit exhibited a 180° phase shift at 4 GHz with a maximum total deviation of 14° over the 0.5 GHz bandwidth and 25° over the 1 GHz frequency bandwidth (3.6–4.6 GHz). The insertion losses in the gold circuit were 5.1 and 6.2 dB for on-state and off-state conditions, respectively, at 4 GHz. However, the insertion losses increased sharply to about 70% over the 0.5 GHz bandwidth. The overall superior performance of superconductor–semiconductor phase shifter than the gold-semiconductor circuit may be mainly due to lower conductor losses, lower surface resistance at lower temperatures, better interface matching of TlCaBaCuO with $LaAlO_3$ substrate and less frequency dependent parasitics in the superconducting circuit.

The design of the phase shifter circuit was not optimized. However, the results of our investigations show that superconductor–semiconductor phase shifter circuit fabricated with TlCaBaCuO high temperature superconductor microstrips does have a higher performance compared to gold circuits at 77 K, proving their usefulness for all superconducting microwave circuit applications.

VI. Acknowledgments

The authors wish to express their appreciation to Dr. R. Leonard, Dr. J. Pouch, Dr. S. Alterovitz, and C. Chorey of NASA Lewis Research Center for their continued support and encouragement. We also wish to thank Dr. P. Boolchand of the University of Cincinnati for his useful suggestions and discussions.

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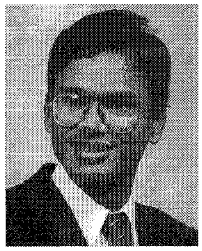

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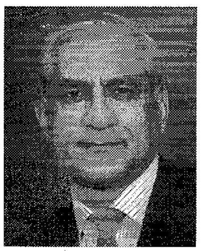

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