

10 GHz HIGH TEMPERATURE SUPERCONDUCTOR PHASE SHIFTER

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Abstract

An HTS phase shifter with a single SQUID device has been developed and tested at 10 GHz. Circuit parameters have been determined, and the performance has been modeled. This HTS single-SQUID phase shifter is the first step toward a multiple device circuit with broadband true-time delay phase shifter performance.

Introduction

In a recent review [1] on the application of superconductivity to antenna subsystems, R.C. Hansen points out that the kinetic inductance [2, 3] effect can provide new ways to electronically scan microwave beams. The unique kinetic inductance effect in superconductors can provide significant slowing of the electromagnetic waves; it can also provide a means for controlling the phase along the transmission line. To date, the only significant changes in phase were induced by changes in temperature [2, 3]; thermal control of the circuit is slow and requires careful regulation. Currents comparable to the critical current can also produce phase velocity changes, but the required currents are huge.

A SQUID can provide an effective way to harness the kinetic inductance effect. This paper describes a single-SQUID HTS phase shifter device that avoids the problems encountered with thermal control. This HTS single-SQUID phase shifter is the first step toward an all HTS, broadband, true-time delay, phase shifter circuit.

This paper will describe a single-SQUID phase shifter circuit, determine the lumped element equivalent circuit, simulate the circuit response, and compare the simulated response to the measured performance.

Circuit Modelling

In this section we determine the circuit values, and calculate the circuit response. While a number of simplifications are made, the approach qualitatively simulates the data.

Figure 1 sketches the layout of the device. A high Q microstrip resonator [4] inductively couples to a SQUID device [5]. A wide range of coupling values, and phase shifts, can be obtained by varying the position of the SQUID device.

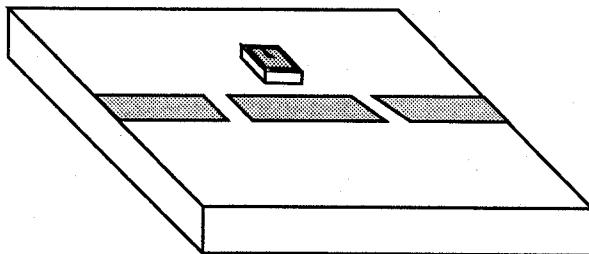
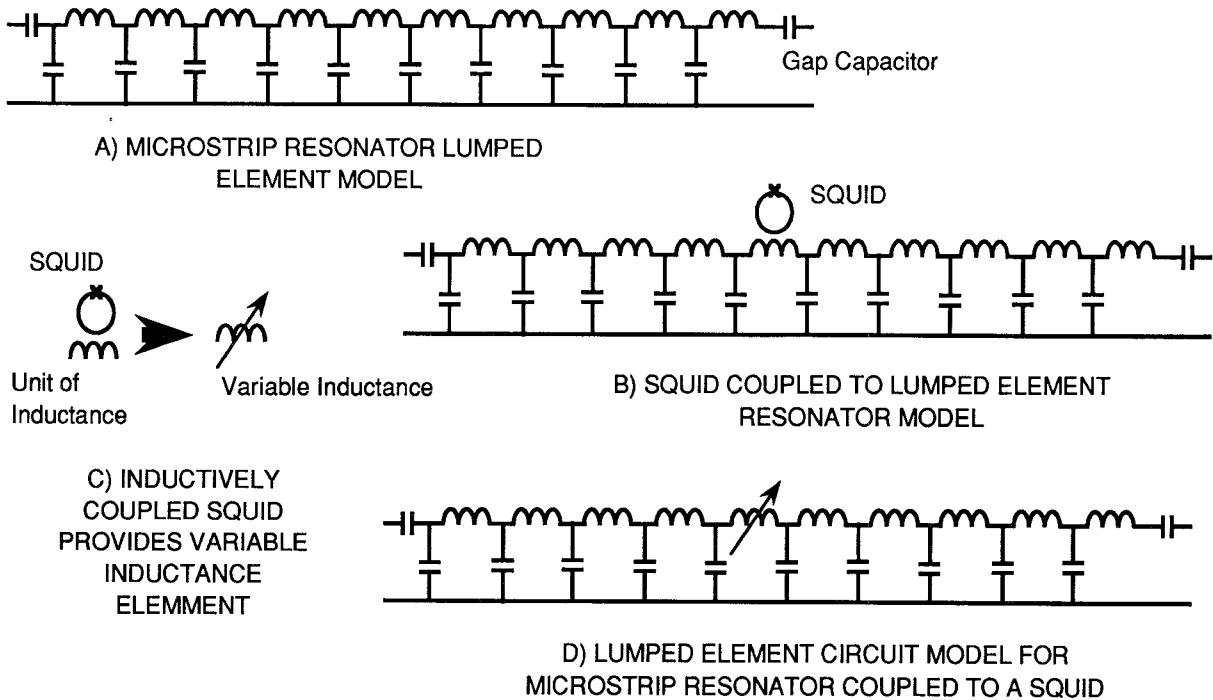


Fig. 1 Circuit configuration showing microstrip resonator coupled inductively to the RF SQUID.

The HTS microstrip resonators [4] were made by depositing $YBa_2Cu_3O_7$ (YBCO) on 20-mil thick $LaAlO_3$ substrates. The gap was designed to produce a loaded Q of about 1000, but when a SQUID device was placed on the resonator, the loaded Q was reduced to about 200. The HTS



circuits were etched in dilute phosphoric acid or an ion-mill. Silver was deposited on the ground plane and at the ends of the microstrip lines.

The HTS SQUID actually rests on the microstrip resonator to maximize coupling values [6]. The SQUID is about 50 mils square, while the resonator is 150 mils X 5 mils. The SQUID chips were fabricated on LaAlO_3 wafers using the step-edge process [5] with laser deposited YBCO films. The wafers were then diced, the devices were screened at 27 MHz, and the devices were mounted near the microstrip resonator.

Values of the lumped element equivalents of the coupling gap, the microstrip resonator, the SQUID coupling, and the SQUID inductance are required for circuit modelling and optimization. The lumped element model is shown in Fig. 2.

The microstrip gap can be modeled with series capacitor. The capacitors affect the external Q of the resonator circuit, and must be determined to fit the measured value of the loaded Q. A smaller capacitor (a larger gap) results in a higher Q, and a smaller bandwidth. The insertion loss as a function of frequency, Fig. 3, shows a loaded Q of about 200.

The microstrip resonator can be modelled as a lumped element ladder with series inductors and shunt capacitors. The microstrip resonator model starts with a capacitively coupled ladder network, Fig. 2a. The circuit model consists of ten inductors and capacitors coupled on the input and the output by a pair of capacitors. The actual resonator was 150 mils long, so the inductor-capacitor L-section corresponds to a 15 mil segment of the transmission line.

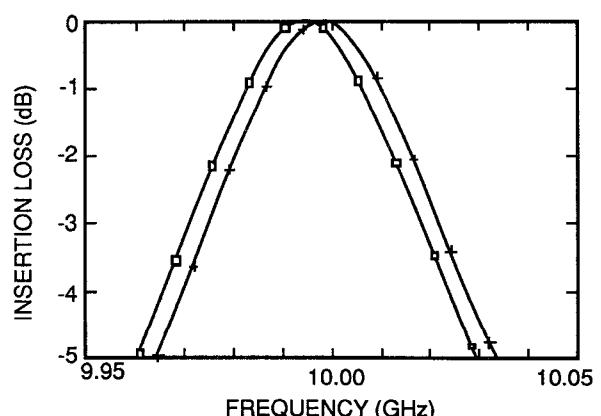


Fig. 3 Calculated insertion loss near resonance for the SQUID coupled to the microstrip resonator. The squares show the insertion loss for the maximum value of the inductance, while the crosses show the response for the minimum inductance.

The SQUID couples inductively to the resonator, and couples most strongly nearest to the device, so it is possible to treat the SQUID coupling to the resonator in a small unit of length (of a single unit inductor), Fig. 2b. The SQUID coupled to the inductor is equivalent to a variable inductor, Fig. 2c. Hence, the final equivalent lumped element circuit with variable inductors is shown in Fig. 2d. Multiple devices, located at specifically chosen points along the transmission line, can be modeled in a similar way.

The values for the total inductance L_T and capacitance C_T of the microstrip resonator are determined by the characteristic impedance Z_0 and resonance frequency ω_0 :

$$L_T = Z_0 / \omega_0 \quad C_T = 1 / Z_0 \omega_0$$

The coupling capacitor is 0.02 pF; the unit capacitance, 0.1 pF; the unit of inductance, 0.23 nH.

The measured coupling is based on experimentally determined values [6] for $k^2 Q = 0.1$, and $\beta = 1$ to 10 (with a typical value of $\beta = 1$). Using the approach of Barone and Paterno [7] one calculates an expression for the change in inductance:

$$\Delta L = \frac{k^2 L_{\text{res}}}{1 + (1/(\beta \cos 2\pi\phi_e))}$$

where L_{res} is the resonator inductance, ϕ_e is the externally applied magnetic flux and

$$\beta = \frac{2\pi L_{\text{SQ}} I_c}{\Phi_0}$$

where L_{SQ} is the SQUID loop inductance,

$$L_{\text{SQ}} = \mu_0 \cdot 1.25 \text{ W nH}$$

μ_0 is the magnetic permeability, W is the washer hole width, I_c is the critical current of the SQUID, and Φ_0 is the flux quantum 4.836×10^{14} Hz/V. From the measured value of $k^2 Q$ and values of β , we determine the change in inductance to be 0.001 nH.

From the expression for the variable inductance, it can be seen that increasing the coupling k increases the magnitude of the variable inductance. As discussed elsewhere [6], a monolithically implemented structure will have a larger k .

In simple terms, the small change in inductance causes a small change in the resonant frequency. This small change in frequency leads to a small change in phase through the circuit.

Figure 4 shows the calculated phase for the parameters discussed above. Two lines show the phase through the resonator in maximum and minimum inductance states. The third line shows the phase change between the two states. The maximum phase difference occurs near the resonance.

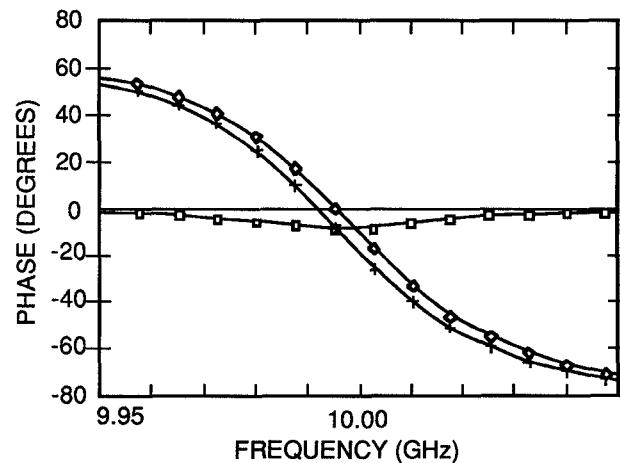


Fig. 4 Calculated phase for the microstrip RF SQUID. The phase of the resonators in the maximum and minimum inductance states are shown (diamonds and crosses), and the difference between them (squares).

Measured Performance

The phase shift was measured by changing the applied magnetic field through many flux quanta, thereby changing a phase shift through many maxima and minima. Measured values for the phase shift are about 10 degrees near resonance, as shown in Fig. 5. This is within a factor of two of the calculated values, Fig. 4.

Figures 5 and 6 were recorded by sweeping the frequency over a narrow range (4 MHz when the 3-dB bandwidth was 200 MHz). An external magnetic field was simultaneously applied. The external field forced many flux quanta to pass through the SQUID loop, and multiple cyclic phase shifts were produced. The peak to peak phase change determined from Figures 5 and 6 is 10 degrees at 6.8 and 58 K.

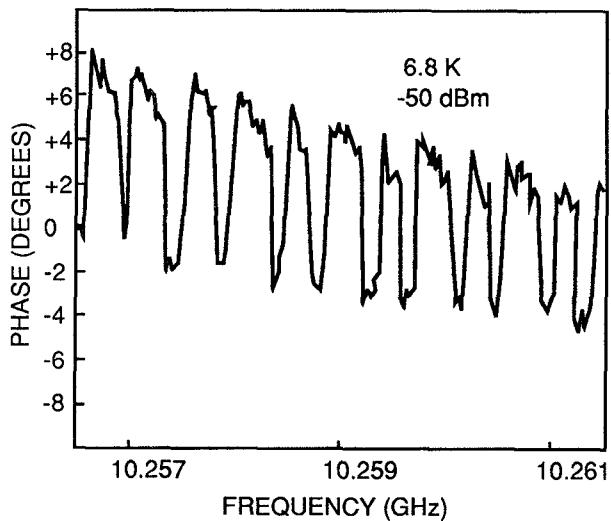


Fig. 5 Measured phase change as a function of frequency and a continuously varying control current at 6.8 K.

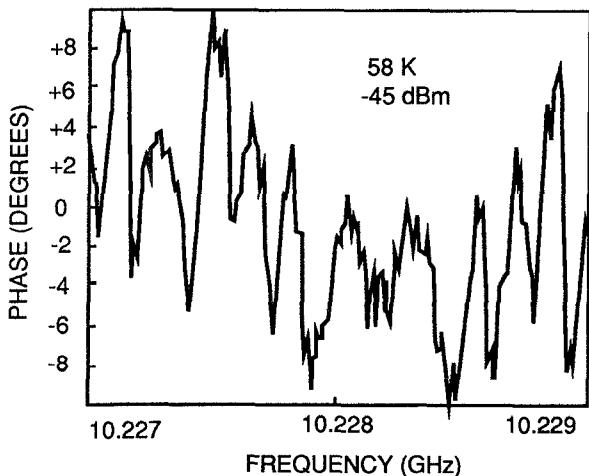


Fig. 6 Measured phase change as a function of frequency and a continuously varying control current at 58 K.

Conclusion

This paper has presented a lumped element equivalent circuit for an HTS single-SQUID phase shifter, and provided a qualitative fit to the measured data. A monolithic implementation of the circuit and a multiple SQUID component will exhibit better performance. Modelling of this HTS single-SQUID phase shifter leads toward an HTS broadband, true-time delay, phase shifter circuit that is under development at TRW.

Acknowledgements

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