A CURRENT CONTROLLED VARIABLE DELAY SUPERCONDUCTING TRANSMISSION LINE

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Abstract

We present a device concept for a current-controlled variable delay superconducting transmission line. The device makes use of the change in kinetic inductance of a superconducting transmission line under the application of a DC bias current. The relevant materials parameters and several promising superconducting materials have been identified.

Introduction

The application of superconductive electronics in mm-wave analog circuits has drawn increasing attention. Among the essential building blocks of such analog circuits is a mm-wave phase shifter. An applied DC current can be used to vary the density of superconducting electrons in a thin film, thereby varying the film's kinetic inductance.[1] In principle, fabrication of transmission lines with such films provides the means for constructing a continuously variable, current-controlled, mm-wave phase shifter. In this paper, we discuss the principles of operation, design considerations and potential limitations of this phase shifter concept. We also present some preliminary measurements on the temperature and current dependence of niobium transmission line resonators operating in the 1 - 20 GHz range that have been studied to explore the practical utility of this device concept.

Device Concept

The equivalent circuit of a variable inductance superconducting transmission line is shown in Fig. 1(a). Here $\mathcal{L}_m$ is the magnetic inductance per unit length associated with the magnetic fields in the line, and $\mathcal{L}_k$ is the kinetic inductance per unit length associated with the kinetic energy of the superconducting electrons flowing in the superconductor.

The current dependence of the kinetic inductance may be derived easily for the case of a spatially uniform current and pair density in the films forming the transmission line. This requires films to be thin with respect to the penetration depth and no magnetic breakdown due to vortex entry at the edge of the film. We shall also assume temperatures near T_c, so that the Ginzburg-Landau equations hold.

If we consider a length L of transmission line in which the total current changes due to a small AC signal current, then the induced voltage due to the kinetic inductance is, in per-unit-length terms,

$$E = \mathcal{L}_k \frac{dI}{dt}$$

From the first London equation we have,

$$-eE = \frac{dp_s}{dt}$$

where p_s is the momentum of the superconducting electrons. Thus the kinetic inductance is,

$$\mathcal{L}_k = \frac{-1}{e}\left(\frac{dI}{dt}\right)^{-1}\frac{dp_s}{dt} = \frac{-m}{e}\frac{dv_s}{dI} \qquad (1)$$

As the velocity of the paired electrons increases, depairing becomes thermodynamically favorable. The extent to which this occurs is a standard result of the Ginzburg-Landau theory,[2,3]

$$f^2 = 1 - \frac{v_s^2}{3v_m^2} \quad \text{where } f^2 \equiv \left|\frac{\Psi}{\Psi_\infty}\right|^2$$

so that f^2 is normalized to unity in the absence of currents and fields. v_m is the velocity corresponding to the maximum supercurrent as a function of velocity. The full expression for the supercurrent is thus:

$$I = -e\sigma|\Psi_\infty|^2 f^2 v_s \qquad (2)$$

where σ is the cross sectional area of the line. The maximum arises as follows: With increasing current I, the kinetic energy of the superconducting electrons increases also. This, however, leads to a decrease in the total superconducting carrier density. If the current is to maintain its value, the velocity of the remaining electrons increases further yet, and so on. Under current bias, the velocity at which the order parameter becomes unstable is v_m, and the corresponding current is, $I_c = I(v_m)$. Physically this effect will appear as a divergent kinetic inductance at the depairing critical current I_c. From Eqs. 1 and 2 we have,[2,3]

$$\mathcal{L}_k = \frac{m}{\sigma e^2|\Psi_\infty|^2}\left(1 - v_s^2/v_m^2\right)^{-1} = \frac{\mu_0\lambda^2}{\sigma}\left(1 - v_s^2/v_m^2\right)^{-1}$$

In any real system, the order parameter Ψ cannot instantaneously adjust to changes in v_s, as we have tacitly assumed so far.[4] In the extreme case of an infinite relaxation time, the condensate density factor in Eq. 2 must be taken as a constant, and thus the result for the kinetic inductance is,

$$\mathcal{L}_k = \frac{m}{\sigma e^2|\Psi_\infty|^2}\left(1 - v_s^2/3v_m^2\right)^{-1} = \frac{\mu_0\lambda^2}{\sigma}\left(1 - v_s^2/3v_m^2\right)^{-1}$$

which is not divergent at I_c.

To obtain $\mathcal{L}_k(I)$ we need only invert $I(v_s)$ along its stable branch. In the small bias current regime we approximate:

$$\frac{v_s}{v_m} \approx \frac{2I}{3I_c}$$

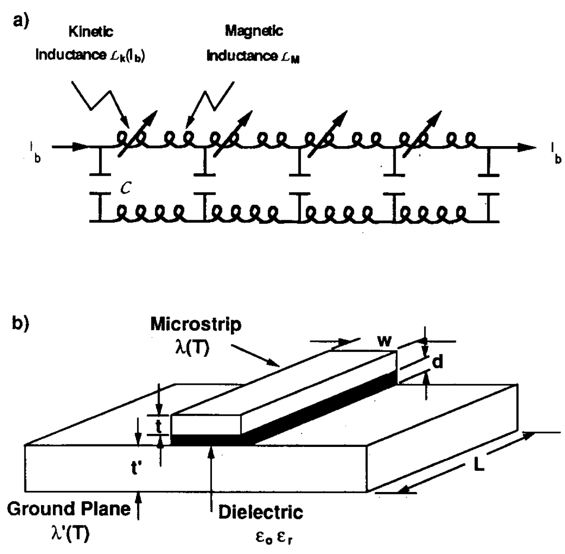

Figure 1. a) Equivalent circuit of a lossless superconducting transmission line consisting of a series inductance and shunt capacitance ladder network. The kinetic inductance, $\mathcal{L}_k$, of the superconducting electrons can be controlled by the application of a DC bias current, or any other depairing mechanism. b) A microstrip realization of this circuit.

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leading to kinetic inductances of,

$$\mathcal{L}_k \approx \frac{\mu_0 \lambda^2}{\sigma}\left[1 + \frac{4I^2}{9I_C^2}\right] \tag{3a}$$

for the instant relaxation case, and,

$$\mathcal{L}_k \approx \frac{\mu_0 \lambda^2}{\sigma}\left[1 + \frac{4I^2}{27I_C^2}\right] \tag{3b}$$

for the infinite relaxation case. At the very high frequencies of interest here, the latter limit will almost certainly pertain.

In the large bias $I \approx I_C$ case with instantaneous response, the kinetic inductance is,

$$\mathcal{L}_k \approx \frac{\mu_0 \lambda^2}{\sigma}\left[\left(\frac{1}{2}\right)\left(\frac{2}{3}\right)\left[1 - I/I_c\right]\right]^{-1/2} \tag{4}$$

which diverges as I approaches I_C.

With the current dependence of the kinetic inductance now known, we may now evaluate the other transmission line parameters. For a lossless line, the phase velocity of the line is given by,

$$v_{phase} = 1/\sqrt{\mathcal{L}C}$$

For a superconductive thin film microstrip line like that shown in Figure 1(b), the capacitance and total inductance per unit length are given by,[5,6]

$$C = \frac{\varepsilon_0 \varepsilon_r w}{d} \text{ and } \mathcal{L} = \frac{\mu_0}{w}\left\{d + \lambda \coth\frac{t}{\lambda} + \lambda' \coth\frac{t'}{\lambda'}\right\}$$

and hence the electrical delay per unit length is,

$$\tau = \frac{\sqrt{\varepsilon_r}}{c}\sqrt{1 + \frac{\lambda \coth\frac{t}{\lambda} + \lambda' \coth\frac{t'}{\lambda'}}{d}}$$

If one or both of the films in the line are made thin compared to the superconducting magnetic field penetration depth, the kinetic inductance contribution can be made to dominate the magnetic inductance from the film and dielectric, and the delay becomes,

$$\tau \approx \frac{\sqrt{\varepsilon_r}}{c}\sqrt{\frac{\lambda^2}{t\,d} + \frac{\lambda'^2}{t'\,d}} \tag{5}$$

Equations 3, 4 and 5 were all obtained in the same limit of spatially uniform currents and pair density in the film. Implicit in Eq. 5 is the dependence of the kinetic inductance on bias current embodied in Eqs. 3(a), 3(b) and 4.

Table I. Materials Parameters and Device Figure of Merit

$$\text{Delay} \approx \sqrt{\frac{\lambda^2}{t\,d}}\, f(I_b/I_c)$$

Material	Tc (K)	λ (μm) (T=0)	$\sqrt{\frac{\lambda^2}{t\,d}}$ *	I_c (mA)
Nb	9.2	0.08	1.1	10.0
NbN	14.0	0.2	2.8	1.0
a-MoGe	7.5	0.5	7.1	0.5
$YBa_2Cu_3O_7$ current flow	90.0			
in ab-plane		0.15	1.4	1.0
along c-axis		1.0	14.0	0.1

* Assume t=100Å, d=0.5μm

In Table I we list some candidate superconducting materials and compare their figures of merit as components of a current controlled phase shifter. The optimum material has a large value for

$$\sqrt{\lambda^2/td}$$

leading to large electrical delays, and a small value of I_C, permitting sensitive control of electrical delay with bias current. It is seen that "dirty" materials with long magnetic field penetration depths, such as amorphous Mo-Ge, are the most promising candidates among conventional superconductors. Interestingly, even more attractive materials are the new high temperature oxide superconductors with the current flow along the c-axis. Fabrication of suitable thin films of these materials presents a formidable challenge, however.

Experiment

To test this device concept, we have fabricated thin film microstrip resonators and studied the dependence of the resonant frequencies on temperature and applied DC current. The resonant frequencies of a line of length L are given by,

$$f_n = \frac{n v_{phase}}{2L} = \frac{n}{2L\tau}$$

and thus are a direct measure of the phase velocity of the line.

The resonators were constructed from two superconducting thin films deposited on separate substrates. One of the films was formed into a 10 μm wide meander line by means of photolithography and ion milling. The other was used as a ground plane. A microstrip was formed by sandwiching a thin dielectric between the two films and pressing the whole assembly together with a suitable clamp. The thin dielectric was obtained by using either a 10 μm mylar sheet, by spinning a layer of photoresist or by evaporating a layer of aluminum oxide onto the ground plane. This latter approach permitted dielectric thicknesses down to 0.27 μm to be obtained. (Dielectric thicknesses were determined by a surface profilometer.) All approaches worked satisfactorily, but the much thinner dielectrics obtained using photoresist or aluminum oxide were particularly attractive because they aid in constructing lines for rapid test purposes in which the kinetic inductance dominates. In practice, a wholly integrated construction would be preferable.

The superconducting niobium films, 500 Å thick, were deposited on single-crystal sapphire (1-102) substrates using electron beam evaporation. The sapphire was argon ion-beam cleaned prior to the deposition.[7] The meander lines were formed using 500 eV argon ion-beam milling. Some degradation of the transition temperature of the niobium was observed following this treatment. Reactive ion etching is likely a more suitable approach.

To make the RF tests, the microstrip assemblies were mounted into a copper RF test fixture and clamped so as to make appropriate contact to the ground plane. RF and bias current contacts were made to the meander line using indium solder applied with an ultrasonic soldering iron. The RF signals are transmitted to the resonator using 50 ohm stainless steel coaxial cables. All other leads are simple twisted pairs. The outer conductors of the coaxial cables are contacted directly to the RF fixture. The microstrip assembly is shown in Fig. 2. The entire RF test fixture can be inserted directly into a standard helium storage dewar for RF measurements at cryogenic temperatures. Temperature control is achieved by means of a heater on the RF fixture and a thermal link to the helium in the form a copper rod extending from the end of the test fixture into the liquid. Temperature measurements are achieved using a silicon diode mounted on the RF fixture in close proximity to the microstrip. Temperature control from 4.2 to 10 K was readily obtained.

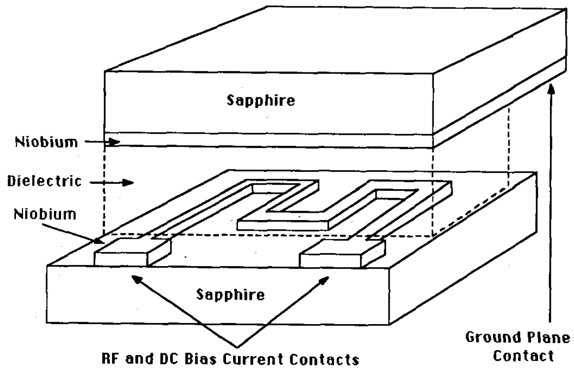

Figure 2. The microstrip assembly, composed of a patterned Nb microstrip and an unpatterned Nb ground plane sandwiching the dielectric material. RF and DC bias connections are made at the front, while ground plane contact is made from behind.

The resonances of the superconducting microstrip were detected by exciting the line using an HP 8340B synthesized frequency source operating in the range from 0.01 to 26.5 GHz and monitoring the reflected and transmitted power using an HP 8757 scalar network analyzer. Resonances associated with the coaxial cables connecting the microstrip to room temperature electronics were eliminated by normalizing the measured reflected or transmitted RF power at any given frequency in the superconducting state by the normal state reading taken just above Tc. This procedure permitted clean observation of the multiple resonances in both return and transmission loss of the microstrip as the frequency was swept. An example is shown in Fig. 3.

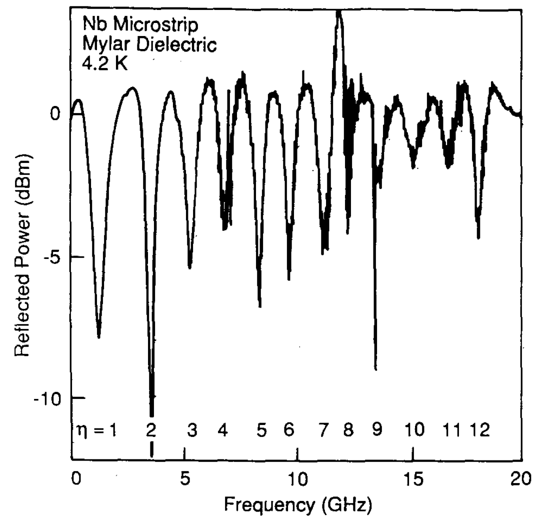

Figure 3. Plot of reflected power versus frequency showing the fundamental and twelve harmonic frequencies of the mylar dielectric microstrip resonator circuit at 4.2 K.

Figure 4 shows the temperature variation of one of the resonant frequencies of two niobium microstrip resonators. The resonator in Figure 4(a) contained a 10 μm mylar dielectric, while that in Figure 4(b) was made with a 0.27 μm aluminum oxide dielectric. From Eq. 5 we see that a microstrip resonator with a smaller dielectric thickness d, all else being equal, will have a larger contribution from its temperature dependent series inductance. Comparison of Figures 4(a) and 4(b) demonstrates this fact. These measurements demonstrate the proper operation of the microstrips and can be used to extract the temperature dependent magnetic penetration depth in superconductors.[5]

Also plotted in Fig. 4 are the calculated values for the resonant frequencies of the superconducting microstrip resonators. This calculation, based on the work of Matick,[6] makes use of the measured T_c and thicknesses of the superconductors, as well as the measured thickness of the dielectric. In addition, the known value and temperature dependence of the magnetic penetration depth for niobium is assumed. The simulation and measured data are in close agreement.

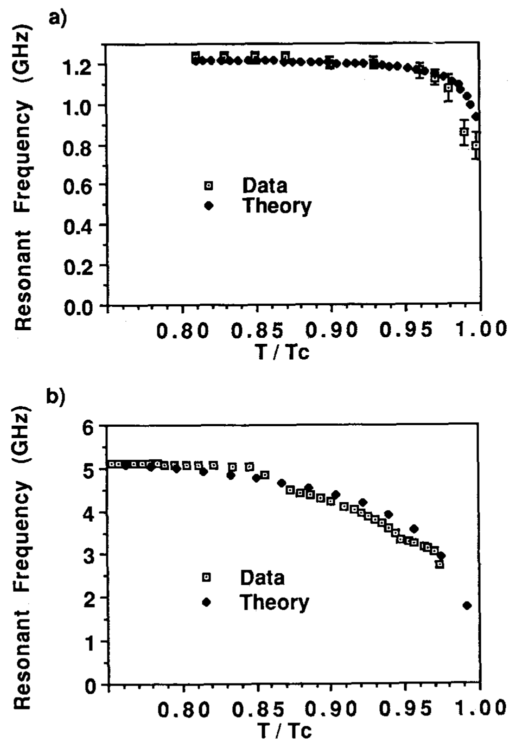

Figure 4. Resonant frequency of a superconducting Nb microstrip circuit versus reduced temperature with a) a 10 μm mylar dielectric, microstrip T_c=8.4 K and b) a 0.27 μm evaporated aluminum oxide dielectric, microstrip T_c=5.5 K. Squares depict measured data, while dots denote the results of the calculation mentioned in the text.

Preliminary attempts to vary the delay of the microstrip transmission line by means of a DC bias current have not yet proven successful. The resonant peaks of the microstrip resonator circuit were not observed to shift with increasing bias current, but instead were seen to reduce their Q-factor, until they disappeared. Critical current densities at which the resonance peaks were lost were found to be in the range 0.3-0.5 x 10^6 A/cm^2 at 4.2 K. The calculated bulk depairing critical current density is 3 to 5 times greater.[3,8] Thus, so far, the maximum current densities achieved in the films were not large enough to produce a measurable change in the kinetic inductance.

The likely reason for the breakdown of superconductivity before a significant peak shift is observed is the existence of strong magnetic fields near the edges of the film which allow flux entry before a significant depairing current density is achieved in the bulk of the film.[9] This explanation is consistent with the observation of hysteresis in the Q-factor of the microstrip resonance as a function of bias current.

One approach to overcoming the problem of the magnetic breakdown of the film is to decrease the dielectric thickness. The corresponding increase in the aspect ratio of the microstrip will make the magnetic field distribution around the film more uniform and minimize the edge effects. Another approach is to use stripline, in which the presence of two ground planes enforces a more uniform magnetic field distribution around the film. A more extreme solution is to make the width of the superconducting film small compared to the transverse penetration depth, λ^2/t.

Another avenue of opportunity is to produce microstrip films composed of an array of Josephson junctions, the inductances of which can be tuned by means of a DC bias current. Examples include extended Josephson junction transmission lines and weak-link coupled granular films, e.g., NbN and even the polycrystalline high temperature superconducting oxides.

Conclusions

We have presented a device concept for a superconductive current biased variable delay transmission line structure which is capable, in principle, of operating up to the terahertz regime. The device makes use of the change in kinetic inductance of superconductors with transport current. The relevant material figures of merit for optimum performance of such a device have been defined, and suitable candidate materials have been identified. The device concept has been tested in niobium technology, where temperature dependent changes in the inductance are easily achieved. The expected DC bias current variable delay has not yet been observed, but niobium is not expected to be the optimum material for such an effect. Suggested improvements include the use of more favorable materials, such as amorphous alloys and oxide superconducting films, and the use of modified microstrip geometries where a closer approach to the depairing critical current density should be possible.

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