A complete analysis of striplines used for Josephson logic and memory circuits

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ABSTRACT

In this paper a thorough investigation on superconducting stripline properties has been made. The stripline properties tike inductance, capacitance, propagation delay, etc. have been estimated for both low-Tc and high-Tc superconducting materials. The effects of stripline properties on attenuation and phase velocity as a function of temperature and frequency are also studied. This work will help scientists and researchers in optimizing the switching speed and circuit dimensions of the Josephson logic and memory circuits before they are fabricated experimentally.

1. INTRODUCTION

The total switching delay of a logic gate consists of the sum of individual delays such as (i) turn-on delay, (ii) rise time delay and (iii) propagation delay. In order to increase the switching speed of a logic gate, it is necessary to reduce the propagation delay.

Striplines are used to interconnect the active devices of both semiconductor and Josephson-junction high-speed integrated circuits [1-4]. In usual practice, the striplines which are used in semiconductor circuits, are made of conventional normal metals and these striplines have problems like more power consumption, long propagation delays, etc. However, the performance of the conventional metal striplines improves a lot at low temperatures. This improvement occurs due to the increase of the conductivity of conventional metal at low temperatures. As the conductivity of conventional metal does not improve drastically at low temperatures, the improvement of stripline properties can not be expected to a very great extent. Due to this fact, at high-frequency operation, the application of conventional striplines is limited. However, after the discovery of superconducting material, the use of superconducting striplines has significantly increased because the problems like high attenuation, long propagation delays, large power consumption, etc. are greatly reduced at high-frequencies. Further, these lines have been already used in designing ultra-high frequency Josephson digital circuits [4]. However, the superconducting striplines are used at liquid helium temperature (4.2K), because the critical temperature (Tc) of the superconducting materials like Pb, Nb, etc. are around that temperature.

It may be noted that the design techniques of conventional metal striplines [1] have been already rigorously investigated and even there is an extensive study regarding the low-Tc superconducting stripline [5-7]. Recently, from 1986 [8] there is a great trend in discovering new superconducting materials of Tcs above liquid nitrogen temperature ($77\,^{o}$K) [9]. As the Tc of these superconducting materials are above $77\,^{o}$K, they may be used as interconnections for both semiconducting (like GaAs) [8,9] and superconducting (like Josephson) devices in the high-frequency operation. The use of these new high-Tc superconducting striplines will improve the performance of both semiconductor and superconducting circuits drastically.

Before making use of any material as a stripline to interconnect the electronic devices it is necessary to know its electronic properties like inductance, capacitance, characteristic impedance, propagation delay and their effects on attenuation and phase velocity as a function of temperature and frequency. Further, in logics and memories based on the SQUID, the inductances play a predominant role in determining the switching speed as well as the circuit dimension, it is essential to have a thorough investigation of the striplines. The present work is an attempt on this line.

In section-2 we have given a brief theory regarding the stripline properties like attenuation, phase velocity, etc. In section-3 we have shown how these parameters vary with temperature and frequency. A comparison is also made between high-lc and low-lc superconducting striplines. Finally, conclusions are given in section-4.

2. BRIEF THEORY AND DESIGN OF A STRIPLINE

A superconducting stripline (Fig.1) consists of a superconducting ground plane and a superconducting strip which is separated by an insulating layer. The parameters involved in designing a superconducting stipline are as follows:

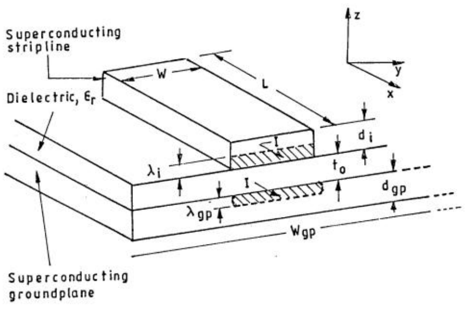


Fig. 1Schematic section of a superconducting stripline.

λ_{gp} = penetration depth of the ground plane superconductor

λ_I = penetration depth of the strip superconductor

d_{gp} = thickness of the ground plane

d_i = thickness of the strip

Tox = thickness of the insulating layer
L = length of the strip
W = width of the strip

In 1960, Swihart [10] derived expressions for attenuation constant and phase velocity V_ϕ of a superconducting stripline with W >> Tox. These expressions are, obtained by solving Maxwell's equations using two-fluid model.

The attenuation

$$\alpha = \mu_o \frac{W^2}{C} \in_r^{1/2} \frac{1}{4Tox} [B]^{-1/2}$$

$$X\, \lambda_i\, \sigma_i 3[\coth(\frac{d_i}{\lambda_i}) + \frac{d_i/\lambda_i}{\sin^2 h(d_i/\lambda_i)}]$$

$$+\lambda_{gp}\, \sigma_{gp} 3[\coth(\frac{d_{gp}}{\lambda_{gp}}) + \frac{d_{gp}/\lambda_{gp}}{\sin^2 h(d_{gp}/\lambda_{gp})}]$$

The phase velocity,

$$V_o = \frac{C}{\in_6 1/2} [B]^{-1/2} \text{ and}$$

$$B = [1 + \frac{\lambda_i}{Tox} \coth(\frac{d_i}{\lambda_i}) + \frac{\lambda_{gp}}{Tox} \coth(\frac{d_{gp}}{\lambda_{gp}})]$$

where C is the speed of light in vacuum, σ_{gp} and 6i are the real components of a complex conductivity $\sigma = \sigma_1 - i\sigma_2$ in the superconducting state.

In the two fluid model σ_1 is given by

$$\sigma_1 = \sigma_n (T/TC)^4$$

However, Kautz [6] has approximated σ_1 in terms of band gap (Δ), temperature (T) and frequency (W), which has good significant in normal practice.

$$\sigma_1 = \sigma_n \frac{2\Delta}{KT} \frac{\exp(\Delta/KT)}{[1+\exp(\Delta/KT)]^2} In(\Delta/hw)$$

In order to obtain an ideal stripline with no attenuation, radiation free, etc., the width.of the stripline (W) should be much greater than the thickness of the insulating layer (Tox) [3]. Under this assumption the total self-inductance of the line,

$$= u_o \frac{LB_1}{W} \text{ where}$$

$$B_1 = [Tox + \lambda_i \coth\frac{d_i}{\lambda_i} + \lambda_{gp} \coth\frac{d_{gp}}{\lambda_{gp}}]$$

and the corresponding capacitance,

$$C = \frac{\in_o \in_r LW}{Tox}$$

At frequencies much less than the superconducting energy gap frequency, the superconducting striplines are very good approximations of ideal lossless lines.

The charaacteristic impedance of the microstrip line, $= 377 \sqrt{\frac{Tox}{\in_r}} [B_1]^{1/2}$

The signal propation delay per unit length.

and the phase velocity of the microstrip line is given by

$$V_\phi = C \sqrt{\frac{T_{ox}}{\in_r}} [B_1]^{-1/2}$$

where C is the velocity of light in vacuum and $\in_r$ is the dielectric constant of the insulating medium.

A superconducting microstrip line of dimension 10 um x 0.7 m (width x length) has been designed using low-Tc as well as high-Tc Y-Ba-CuO superconductors. The parameters considered for design are given in Table-I. The value of the penetration depth, λ (T) for Y-Ba-Cu0 superconductor has been taken from Reference [11] . The critical temperature and the normal state conductivity of this superconductor are 86K and $1x10^6$ m^{-1} Ω^{-1} respectively. Further, the superconducting band gap (Δ) the normal state conductivity (σ_n) and the penetration depth (λ (0)) are related by the expression,

$$\lambda(0) = [\hbar / \pi \mu_o \Delta(0) \sigma_n]^{1/2}$$

The termperature -- depedent penertraion depth is given by

$$\lambda(T) = \frac{\lambda(0)}{[1-(T/TC)^4]^{1/2}}$$

3. RESULTS AND DISCUSSIONS

The attenuation and phase velocity as functions of temperature and frequency for a PbInAu based superconductor stripline are shown in Figures 2.(a)-(d). These curves are similar to those obtained by Kautz [6]. This gives confidence to our theoretical approach that we have adopted here in designing striplines. In Fig.2.(a) the attenuation-versus-frequency curves are drawn for different temperatures of the designed stripline. Attenuation increases almost linearly with applied frequency upto the energy gap frequency and there is a sudden raise in attenuation at that frequency. The variation of attenuation with temperature for different operating frequencies are shown in Fig.2. (b). It can be observed that at T > Tc the superconductor will become normal and there is a sudden raise in attenuation.

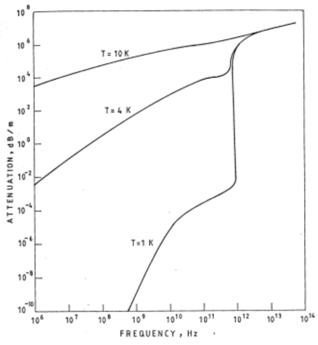


Fig.2a Variation of attenuation with frequencies at different temperatures for a PbInAu based stripline.

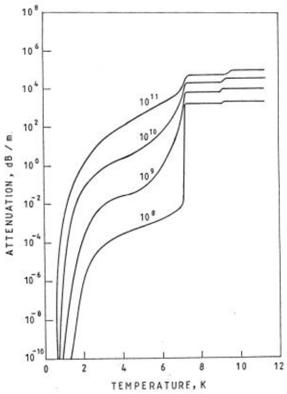


Fig. 2b Variation of attenuation with temperature at different frequencies for a PbInAu based stripline.

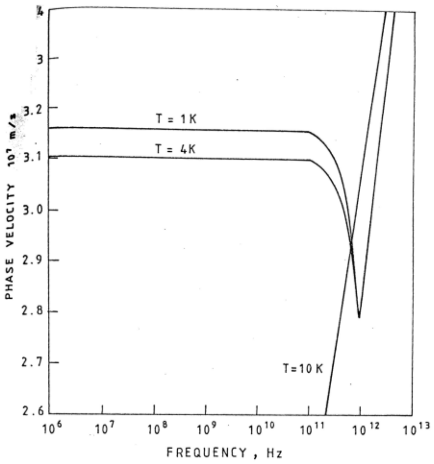
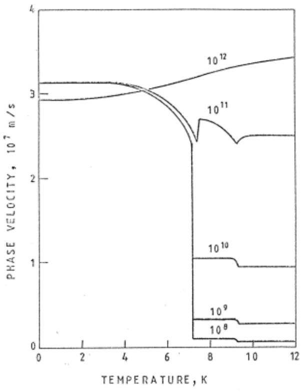


Fig. 2C: Variation of phase velocity with frequency at different temperature for a PbInAu based stripline.



Fig, 2d : Variation of phase velocity with temperature at different frequencies for a PbInAu based stripline.

The phase velocity is constant and independent of applied frequency upto one-third of the gap frequency (as shown in Fig.2(c)),after which the normal losses come into picture resulting in a decrease in the phase velocity.

The PbInAu based striplines are used to design inductance and interconnections of Pb-alloy Josephson logic gates and memory circuits. Since the present thesis deals with the design of logic and memory circuits using Nb/Alox/Nb Josephson technology, it is also necessary to have a thorough investigation of its stripline (Nb/Nb $_2$ O $_5$ b + Si0/Nb) properties. Fig. 3(a)-(d)) shows stripline properties like attenuation and phase velocity as functions of temperature and frequency for a Nb based superconductor stripline.

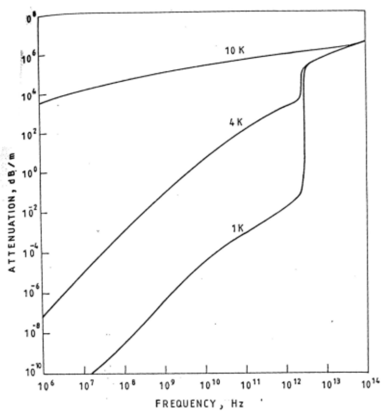
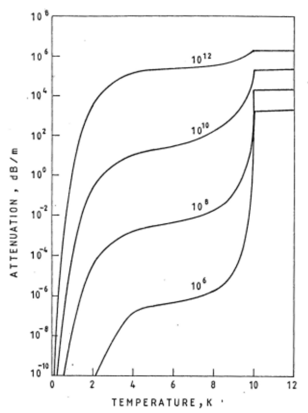
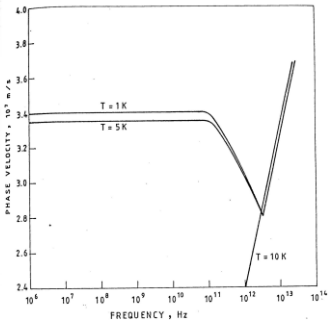


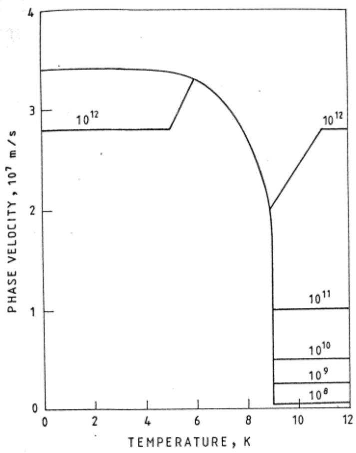
Fig. 3a : Variation of atteneaution with frequencies at different temperatures for a Nb based stripline.



F.g. 3b : Variation of attenuation with temperature at different frequencies for a Nb based stripline.



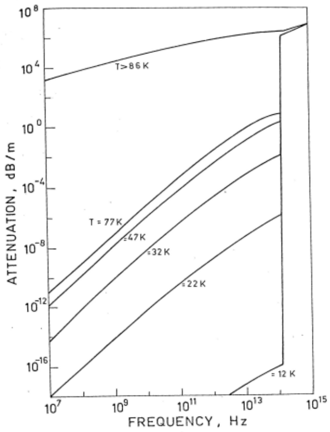
F.g. 3c : Variation of phase velocity with freqneucy at different temperature for a Nb based stripline.



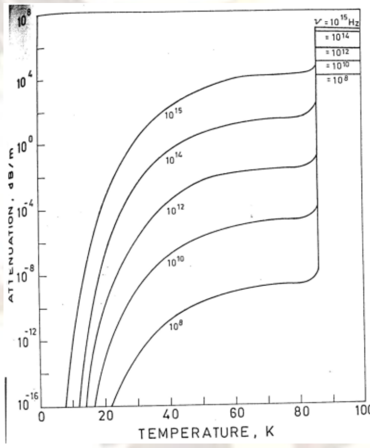
Fg. 3d : Variation of phase velocity with tmeprature at different frequencies for a Nb based stripline.

It can be observed from Fig.2(a)-(d) and Fig.4.3(a)-(d) that at Tow frequencies, the attenuation in the case of PbJnAu striplines is 10^{-2} dB/m (at 4.2° K) whereas for Nb based stripline it is 10^{-7} dB/m (at 4.2° K). Further, the phase velocity is 3.1 x 10^7 m/s and 3.4 x 10^7 m/s for PbInAu and Nb based striplines respectively. It can also be observed from the two set of curves that Nb based striiplines have better prospects than Pb-alloy striplines.

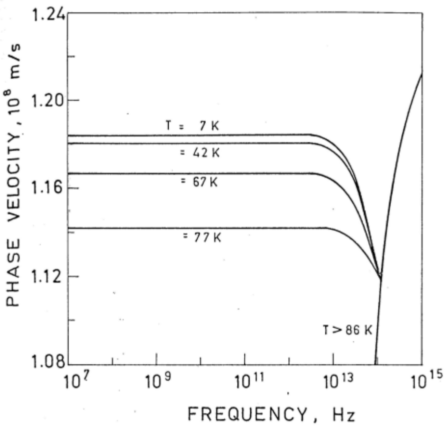
Further, we have studied stripline properties of recently developed high-T-c Y-Ba-Cu0 superconductor [12]. Fig 4 ((a)-(d)) shows the attenuation and phase velocity as function of temperature and frequency for a Y-Ba-Cu0 superconductor stripline. It can be observed from the plottings that the curves are almost similar to those obtained for low-Tc striplines. The variation of atteunation with temperature for different operating frequencies are shown in Fig.4(b). It can be observed that at T > 86K, the superconductor will become normal and thereby there is a sudden rise in attenuation.



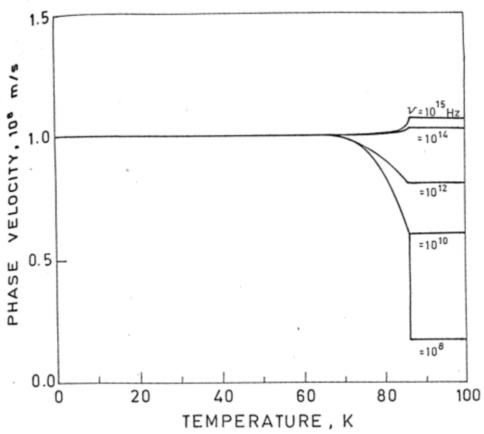
F.g 4a : Variation of attenuation with frequencies at different temperatures for high – Tc Y-Ba-Cu0 superconductor based stripline.



F.g. 4b : Variation of attenuation with temprature at different frequencies for a high-Tc Y-Ba-Cu0 superconductor based stripline.



Fg. 4c : Variation of phase velocity with frequency at different temperatures for a high-Tc Y-Ba-Cu0 superconductor based stripline.



F.g. 4d : Variation of phase velocity with temperature at different frequencies for a high-Tc Yba-Cu0 superconductor based stripline.

The phase velocity for a high-Tc Y-Ba-Cu0 superconductor stripline obtained as $1.1x10^8$ m/s which is higher than that obtained for a low-Tc superconductor stripline. The higher phase velocities of these high-Tc superconductor striplines will permit low transmission delays compared to low-Ic superconductor striplines. The microstrip line properties like inductance, capacitance, characteristic impedance and transmissing delay for a high-Tc Y-Ba-Cu0 superconductor microstrip line have been calculated and shown in lables-II.

The various properties of the high-Tc Y-Ba-Cu0/Si0/Y-Ba-Cu0 microstip line are compared with those of low-Tc PbAu/Si0/Pb and PbInAu/$Nb_2 0_5$ /Nb microstrip lines (Table-II). It can be observed from Table-II that the microstrip lines made of Y-Ba-Cu0 superconductor have the similar type properties like that of low-Tc superconducting microstrip lines. The characteristic impedance, Z = 50 ohms obtained in the case of Y-Ba-Cu0 superconductor microstrip line will have a better matching for coupling this microstrip line with the normally used semiconductor as well as superconducting circuits [13].

Further, in Fig. 5a we have shown the dependence of inductance on the width, for a l0 μm length of the stripline using two different technologies PbInAu/$Nb_2 0_5$ + Si0/Nb and Nb/$Nb_2 0_5$ +Si0/Nb. It is apparent from the Fig. 5a that as the width of the stripline increases the inductance value decreases. Further, in Fig. 5b we have shown the dependence of inductance on the length for a 2 μm width of the stripline using the two different technologies.

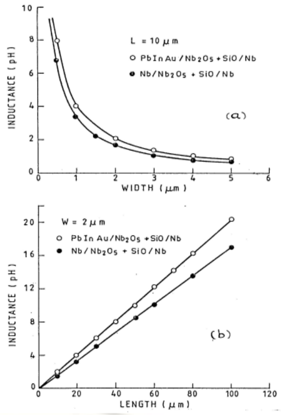


Fig. 5a The dependance of inductance on width fora 10μm length of stripline using two different technologies
Fig.5bThe depednance of inductance on length for a 2μm width of a stripline using two different technologies
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As the length increases the inductance value of the stripline increases. In a similiar way, we have studied the dependence of width on the capacitance of the stripline as well as the dependence of length on the capacitance of the stripline. These are shown in the Fig. 6a and 6b respectively.

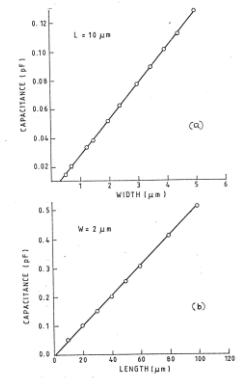

Fig. 6a: The depedence of capacitance on width for a 10μm length of the stripline.
Fig. 6b: The depedence of capacitance on length for a 2μm width of the stripline.

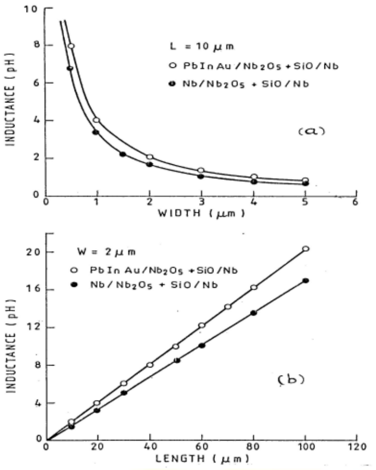

Fig.7aThe dependence of propagation delay on the width for a 10µm length of the stripline using two different technologies.
Fig.7bThe dependence of characteristic impendance on length for a 2µm width of the stripline using two different technologies

Also, in Fig. 7a we have shown the dependence of width on the propagation delay for a 10 μ m length of the stripline using the two different technologies. It is apparent from the curves that Nb based stripline (to be used as in interconnections in Nb/A10 x/Nb Josephson logic circuits) has a low propagation delay compared to PbInAu based stripline (to be used as interconnections in Pb-alloy Josephson logic circuits). Due to this fact the Nb/A10x/Nb Josephson logic circuits are expected to have high switching speeds. Finally, in Fig. 7b we have shown the dependence of length on the characteristic impedance for a 2 μ m width of the stripline using two different technologies. The curves 5-7 are useful in critically determining and optimizing the microstripline parameters such as inductance, capacitance, characteristic impedance, propagation delay, etc. In Table-III we have obtained parameters of a 2 μ m widthand 10 μ m length of PbInAu/Nb205+SiO/Nb and Nb/Nb205+SiO/Nb striplines. It is apparent from the results that Nb based stripline has better features over PbInAu based stripline. We have, therefore, selected Nb/Nb205+SiO/Nb striplines in designing the inductance and interconnections that are used in Nb/A10x/Nb Josephson logic and memory circuits.

TABLE – I

VARIOUS PARAMETERS AND DIMENSIONS INVOLVED IN DESIGNING THE MICROSTERIP LINE

Parameter	MICROSTRIP LINES		
	PbAu/ Si0/Pb	PbInAu/ Nb_2O_5/Nb	Y-Ba-Cu0/ Si0/Y-Ba-Cu0
Operating Temperature (T)	4.2°K	4.2°K	77°K
λ_{gp} (nm)	48.5	85.3	130
λ_i (nm)	75.5	135	130
T_{ox} (nm)	880	100	880
d_{gp} (nm)	450	400	300
d_i (nm)	450	400	300
ϵ_r (nm)	5.7	29	5.7

TABLE – II

VARIOUS PARAMETERS OF THE DESIGNED MICROSTRIP LINE

PARAMETER	MICROSTRIP LINES		
	PbAu/ Si0/Pb	**PbInAu/ Nb_2O_5/ Nb**	**Y-Ba-Cu0/Si0/ Y-Ba-Cu0**
$\mathcal{L}$ (nH)	88.3	28.2	101.67
$\mathcal{C}$ (pF)	40.1	18 x 10^3	40.1
Z_o ( )	47	1.25	50
τ (nS)	2.7	32.2	2.88
V_ϕ (m/S)	3.7 x 10^7	0.31 x 10^7	3.47 x 10^7

TABLE – III

VARIOUS PARAMETERS OF THE DESIGNED MICROSTRIP LINES FOR A WIDTH OF 2µ AND A LENGTH OF 10µM

PARAMETER	MICROSTRIP LINES	
	PbInAu/ Nb_2O_5+ Si0/Nb	**Nb/Nb_2O_5 + Si0/Nb**
$\mathcal{L}$ (pH)	2.0	1.7
$\mathcal{C}$ (pF)	0.05	0.05
Z_o (Ω)	6.2	5.75
τ (pS)	0.32	0.29
V_ϕ (m/S)	3.1 x 10^7	3.38 x 10^7

4. CONCLUSIONS

The low-Tc as well as high-Tc (Y-Ba-Cu0) superconductor striplines have been designed theoretically and studied properties, like attenuation and phase velocity as functions of temperature and frequency are studied. It is found that the nature of the high-Tc Y-Ba-Cu0 stripline properties are similar to that of low-Tc superconductor striplines. These high-Tc superconductor striplines have advantages over low-Tc superconductor striplines because of the high energy gap frequency thereby the frequency of operation can be more for high-Tc superconductor striplines. Further, the phase velocity of a high-Tc superconductor stripline is higher than that of a low-Tc superconductor stripline, which leads to small propagation delays. Since these high-Tc striplines are operated at liquid nitrogen temperature, they may be used as interconnections for both superconductor (Josephson) as well as semiconductor (GaAs) digital logic and analog circuits.

The various properties of the high-Tc

microstripline (Y-Ba-Cu0/Si0/Y-Ba-CuO) are compared with those of low-Tc microstriplines such as PbAu/Si0/Pb and PbInAu/Nb $_2$ 0 $_5$ /Nb in Table-II. It can be observed from Table-II that the microstrip lines made of Y-Ba-Cu0 superconductor have the similar type properties like that of low-Tc superconducting microstrip lines. The craracteristic impedance, Z = 50 ohms obtained in the case of Y-Ba-Cu0 superconductor microstrip line will have a better matching for coupling this microstrip line with the normally used semiconductor as well as the superconducting circuits.

Further, in Table-III we have obtained parameters of a 2 μm width and 10 μm length of PbInAu/Nb $_2$ 0 $_5$ +Si0/Nb and Nb/Nb $_2$ 0 $_5$ +Si0/Nb striplines. It is found that Nb based stripline has better features over PbInAu based stripline. Due to this fact we have selected Nb/Nb $_2$ 0 $_5$ +Si0/Nb striplines in designing the inductance and interconnections that are used in Nb/A10 x/Nb Josephson logic and memory circuits.

Acknowledgements

The greatest thanks to my guide ,Prof. Dr.J. C. Biswas, Ex-Professor, ECE Department , Indian Institute of Technology , India for his quality oriented suggestions made crucial impact on the value and importance of this work. I would like to acknowledge Prof.C.L.R.S.V. Prasad, Prinipal GMR Institute of Technology, Rajam, A.P,India for his constant encouragement to finish this work.

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