Superconductor Stripline test.

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IT-CDT 2018-1

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Change Record

Revision	Date	Affected Paragraphs(s)	Reason/Initiation/Remarks
A	2018-01-15	All	First Issue

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Simulation Tests:

1. Introduction

Cryogenic 3 dB and 90º directional couplers (usually referred to as hybrids) have been developed by Yebes for several frequency bands below 16 GHz. These have been used in the IF stage of the 2SB mmW receivers and in balanced amplifier configurations. The balanced amplifier configuration is introduced to improve the poor match usually found in wideband cryogenic amplifiers optimized for low noise operation. It is clear that for these two applications, reducing the insertion loss of the hybrid is of primary importance since the dissipative loss contributes to the overall noise of the system.

Until now the hybrids developed in Yebes were based on coupled lines structures in stripline technology and were built using soft substrates with electrodeposited copper. One possibility for drastically reducing the insertion loss is substituting copper by a superconductor since losses are usually dominated by the finite conductivity of the substrate metallization in common stripline and microstrip structures at microwave frequencies.

Sumitomo coolers can obtain working temperatures close to 4 K at which some common metals (Pb, Nb) become superconductors. In particular, the transition temperature of Pb and certain solder alloys like SN60 is close to 7K (see table 1). Unfortunately copper lines covered with SN60 solder in only one side has not shown the RF loss reduction of superconductors and is not of interest for practical applications.

2. Experiment

This report presents the results of two experiments with weakly coupled transmission line series resonators of Pb and SN60, cooled below superconductor transition temperature

The resonator (see

Figure 1) is a 50 Ω section of strip line,[1], made of pure Pb[2] or SN60 solder[3]. This resonant section is weakly coupled[4] to the copper input/output lines with two capacitive gaps[5]. The dielectric used is RT/Duroid 6002[6]. The outer chassis is made of copper[7] for higher efficienty cooling since some aluminum alloys have shown very poor thermal conductivity at temperatures below 15 K.

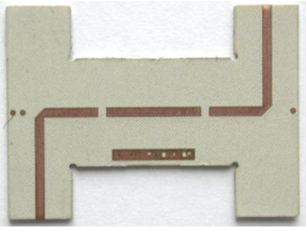

Figure 1. Resonator in stripline (copper).

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[1] Its length determines the resonant frequency. As a first approximation, the physical length is half wavelength of the desired resonant frequency

[2] Pure Pb electrical resistivity at 295 K = 20.9 μΩ cm = 4.78 106 S/m (from [1] pp 567).

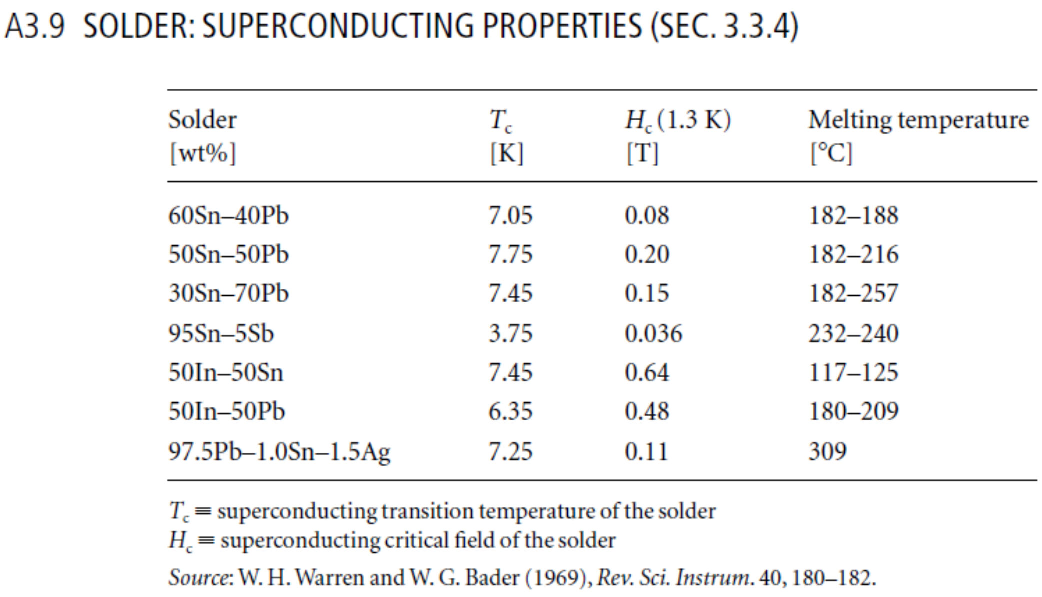
[3] The strip was made by compression of a piece of wire of the corresponding material and cutting it to the desired final dimensions using a scalpel.

[4] A maximum $|s_{21}|$ of -25 dB was estimated for a gap length of 0.4 mm

[5] The abrupt discontinuity produces an increment of the effective length so the final physical length of the resonant section must be smaller, around 10.57 mm in our resonators, to achieve a resonant frequency at 8 GHz.

[6] Consisting in PTFE loaded with Al_2O_3 with a 17 μm of electrodeposited copper.

7 Copper OFHC gold plated with 1 μm soft Au.



A3.9 SOLDER: SUPERCONDUCTING PROPERTIES (SEC. 3.3.4)

Solder [wt%]	T_c [K]	H_c (1.3 K) [T]	Melting temperature [°C]
60Sn–40Pb	7.05	0.08	182–188
50Sn–50Pb	7.75	0.20	182–216
30Sn–70Pb	7.45	0.15	182–257
95Sn–5Sb	3.75	0.036	232–240
50In–50Sn	7.45	0.64	117–125
50In–50Pb	6.35	0.48	180–209
97.5Pb–1.0Sn–1.5Ag	7.25	0.11	309

$T_c \equiv$ superconducting transition temperature of the solder
$H_c \equiv$ superconducting critical field of the solder

Source: W. H. Warren and W. G. Bader (1969), *Rev. Sci. Instrum.* 40, 180–182.

Table 1. Solder superconducting properties. Table taken from [1]

Note that if the resonator is very weakly coupled, the loaded and unloaded Qs are similar and the insertion loss at resonant frequency is quite high. The expression for the insertion loss is given by:

$$InsertionLoss(dB) = -20 \cdot \log\left(1 - \frac{Q_L}{Q_U}\right)$$

where Q_L is the loaded Q and Q_U is the unloaded Q. Q_L can be easily determined by measuring the relative bandwidth at -3dB of the resonance. On the other hand insertion loss at the resonant frequency is directly obtained by the transmission measurement. Therefore, Q_U can be obtained as:

$$\frac{Q_L}{Q_U} = 1 - 10^{\frac{-InsertionLoss(dB)}{20}} \qquad Q_U = \frac{Q_L}{1 - 10^{\frac{-InsertionLoss(dB)}{20}}}$$

Note that even in the case of perfect (lossless) conductors Q_U is ultimately limited by the dielectric loss. In the case of RT/Duriod 6002 the value of tan δ given by the manufacturer for ambient temperature is 0.0012@10GHz. The maximum Q which could be theoretically obtained is:

$$\max Q_U = \frac{1}{\tan\delta} = \frac{1}{0.0012} = 833$$

As values of Q_U of the order of 1000 are obtained in our experiments below the critical temperature, we assume that the tan δ of the dielectric at cryogenic temperature should have a value of ≈0.001, assuming negligible contribution of conductor losses.

In this work the transmission data measured in the cryostat is compared with a simple ADS resonator model. The value of the coupling capacitors are easily determined by fitting the overall transmission response in the whole band. Then, the exact value of resonator length is tuned to obtain the transmission peak in the right position. Finally, the conductor loss can be adjusted to fit the measured relative bandwidth at -3 dB. An example of a typical result in the whole band (from Pb resonator at ambient temperature) is presented in the Figure 2:

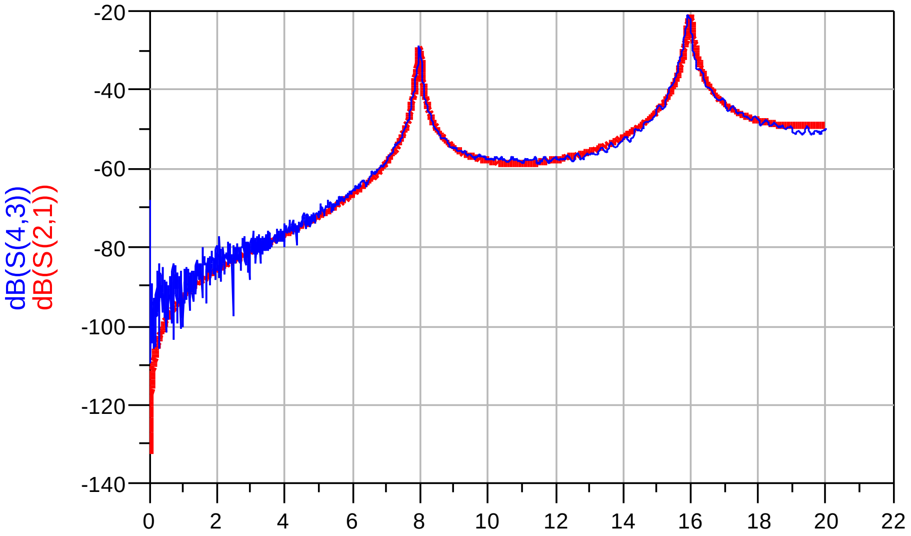


Figure 2. Simulation vs measurement of the Pb resonator at T=290 K.

3. Conclusions of the test:

– Losses at ambient temperature are reasonably well predicted by the ADS SLIN model including nominal metal line conductance and tan δ of the dielectric. The dominant effect is the conductor loss.

– Losses in the superconductor state are modeled with good accuracy with an ideal transmission line resonator with a lossless conductor and a dielectric with its loss modeled using its tan δ. The value of tan δ is set to 0.001 (instead of 0.0012) to obtain a better fit. It may be possible that the dielectric loss is slightly reduced at cryogenic temperature.

– The transition to the superconductor state for Pb and SN60 is close to 7 K. As the critical temperature is approached, the 1 Hz temperature oscillation of the cooler is easily observed as drastic changes in the shape of the resonance peak.

– Once in the superconductor state (below the critical temperature), there is some Q improvement by reducing the temperature.

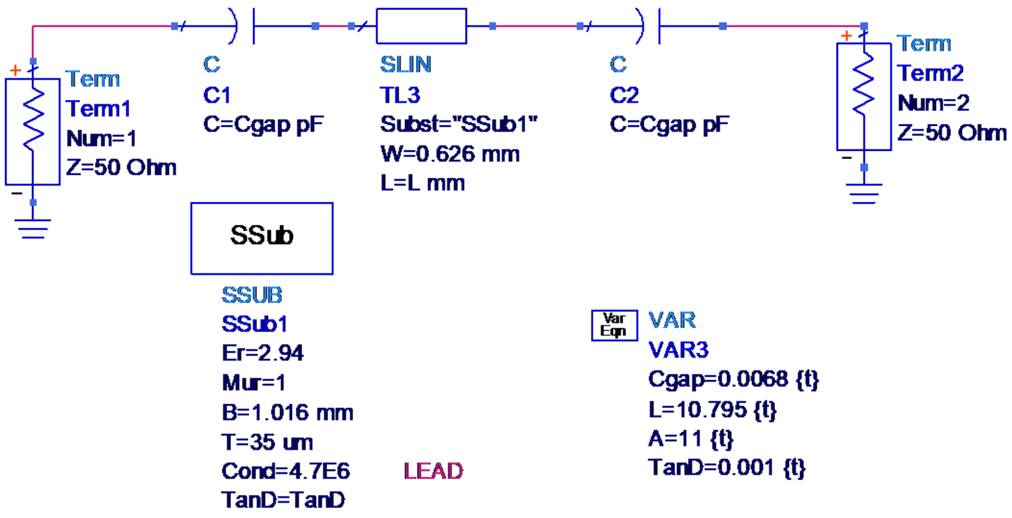
– The values of the loaded and unloaded Q in the following graphs are obtained from the 3 dB bandwidth and insertion loss.

– Copper lines covered with SN60 solder in only one side has not shown the RF loss reduction of superconductors and is not of interest for practical applications.

4. References

[1] *Ekin, Jack*, “Experimental techniques for low-temperature measurements: cryostat design, material properties and superconductor critical-current testing,” Oxford university press, 2006.

Superconductor Stripline Resonator (Pb line T=290K)



Term
Term1
Num=1
Z=50 Ohm

C
C1
C=Cgap pF

SLIN
TL3
Subst="SSub1"
W=0.626 mm
L=L mm

C
C2
C=Cgap pF

Term
Term2
Num=2
Z=50 Ohm

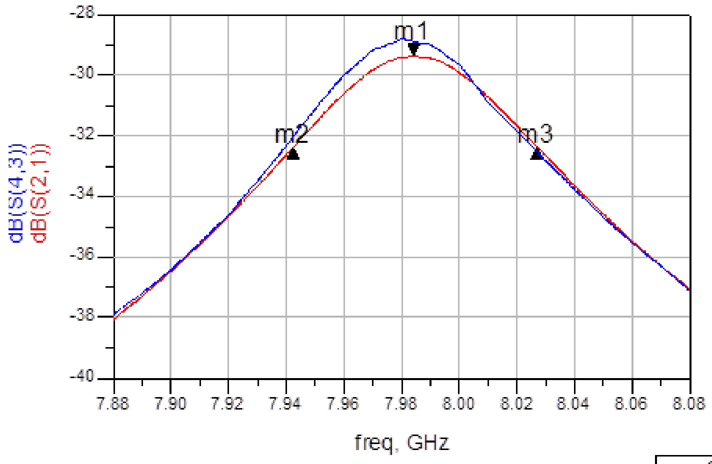
SSub
SSUB
SSub1
Er=2.94
Mur=1
B=1.016 mm
T=35 um
Cond=4.7E6
LEAD
TanD=TanD

VAR
VAR3
Cgap=0.0068 {t}
L=10.795 {t}
A=11 {t}
TanD=0.001 {t}

```
m1
freq=7.984GHz
dB(S(2,1))=-29.363
Max
```

```
m2
ind offset=-4.180E7
target dep offset=-3.000
actual dep offset=-3.002
Offset Mode ON
```

```
m3
ind offset=4.270E7
target dep offset=-3.000
actual dep offset=-3.007
Offset Mode ON
```

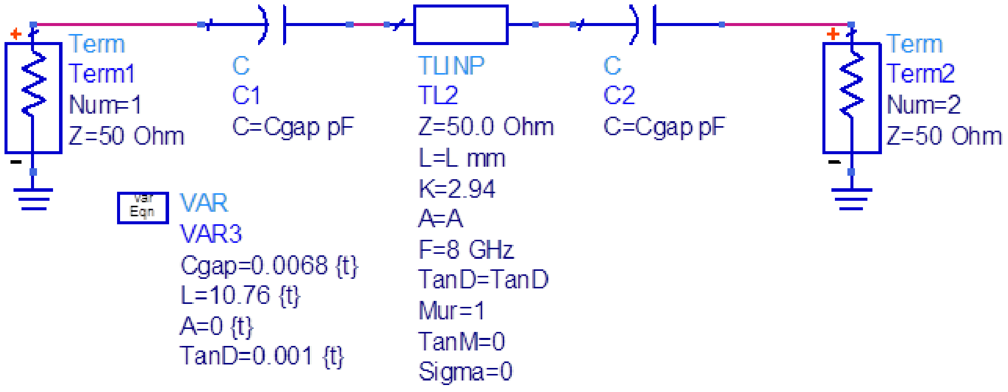


QL	QU
94.488	97.816

Eqn QL= indep(m1,1) / (indep(m3,1) - indep(m2,1))

Eqn QU=QL/(1-10**(m1/20))

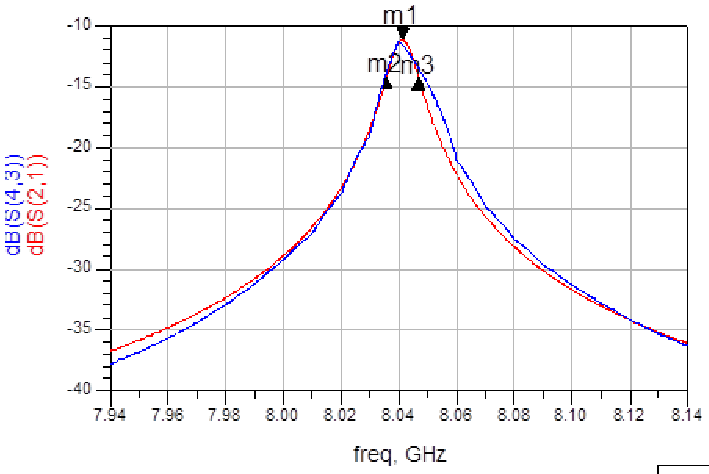
Superconductor Stripline Resonator (Pb line T=4.6K)



m1
freq=8.041GHz
dB(S(2,1))=-11.118
Max

m2
ind offset=-5.500E6
target dep offset=-3.000
actual dep offset=-3.054
Offset Mode ON

m3
ind offset=5.500E6
target dep offset=-3.000
actual dep offset=-3.076
Offset Mode ON

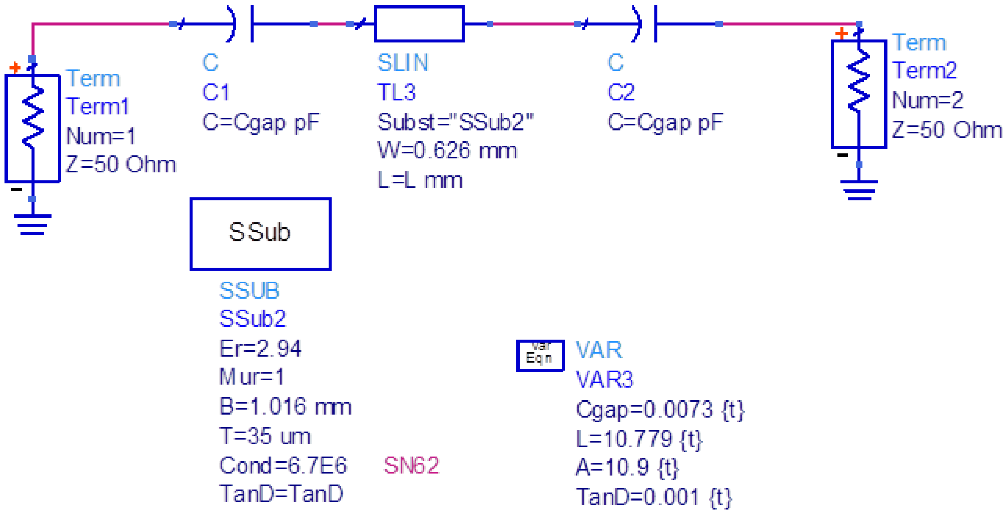


QL	QU
731.018	1012.538

Eqn QL= indep(m1,1) / (indep(m3,1) - indep(m2,1))

Eqn QU=QL/(1-10**(m1/20))

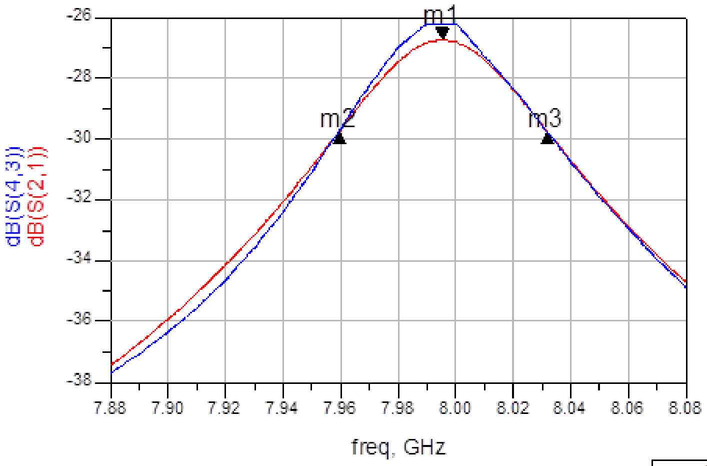
Superconductor Stripline Resonator (SN60 line T=290K)



m1
freq=7.995GHz
dB(S(2,1))=-26.749
Max

m2
ind offset=-3.580E7
target dep offset=-3.000
actual dep offset=-3.003
Offset Mode ON

m3
ind offset=3.650E7
target dep offset=-3.000
actual dep offset=-3.007
Offset Mode ON

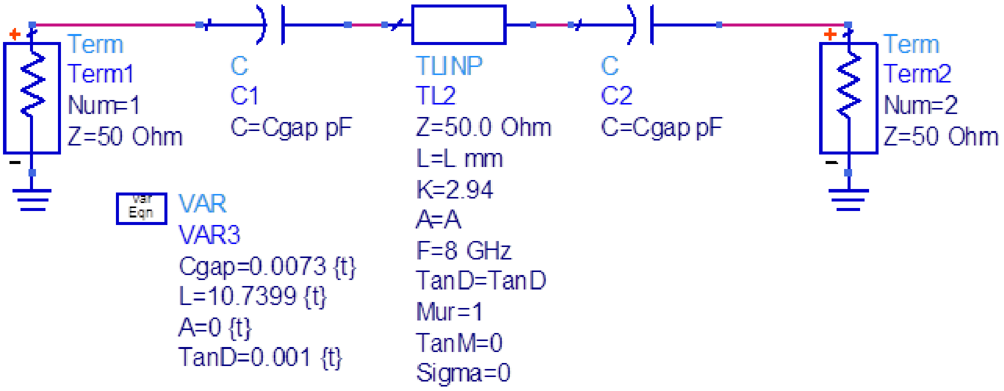


QL	QU
110.584	115.913

Eqn QL= indep(m1,1) / (indep(m3,1) - indep(m2,1))

Eqn QU=QL/(1-10**(m1/20))

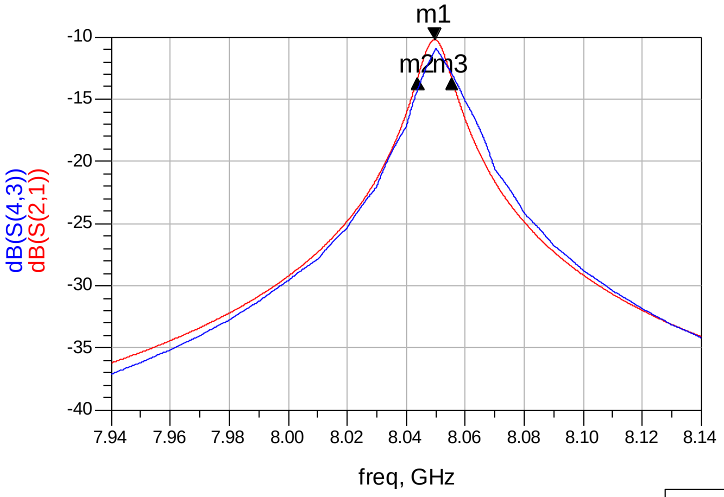
Superconductor Stripline Resonator (SN60 line T=4.5K)



m1
freq=8.050GHz
dB(S(2,1))=-10.224
Max

m2
ind offset=-5.700E6
target dep offset=-3.000
actual dep offset=-3.035
Offset Mode ON

m3
ind offset=5.700E6
target dep offset=-3.000
actual dep offset=-3.039
Offset Mode ON



QL	QU
706.105	1020.645

Eqn QL= indep(m1,1) / (indep(m3,1) - indep(m2,1))

Eqn QU=QL/(1-10**(m1/20))