SuperMix Aided Design of SIS Tunnel Junction Heterodyne Receivers

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Caltech

Fabrication Tolerances

So you have the perfect design... The questions are:

Q: How will fabrication tolerances affect the performance of your mixer?

A: One can use **SuperMix** to estimate the effect of variations from optimal for the critical parameters.

Q: How can one compensate for deviations from optimal fabrication parameters?

A: Using variations in the junction area is commonly used for compensation. **SuperMix** can be helpful in figuring just how much you have to tweak the junction area to regain nearly optimum performance even with the mismatched parameters. Table 1. shows the required level of area compensation and the residual performance degradation based on 10% variation in the given parameter. Table 2. shows the effects of typical fabrication tolerances. A ±15% variation from the nominal area is optimal. The residual performance degradation based on 7.5% residual area mismatch is a mere 0.7K in mixer noise and ca. 0.1dB in IF flatness.

Property	**E**	**Δχ**	**ΔT (K)**
SiO Thickness	-0.768	10.1%	1.0
εr	0.327	12.2%	0.6
ρ⊥	-0.069	0.4%	
RnA	-0.019	7.6%	0.5
C_junction	-0.097	7.6%	0.5
Area		24.0%	0.9

Table 1. Effect of Compensated Property Variations based on a 10% change from optimal values. Data columns: 1. Compensating Junction Area Elasticity (defined as dA/dP P/A for property P and area A); 2. Increase in the error function as measured in the opyimization scheme (Tmix and IF flatness); 3. Approximate increase in mixer noise temperature.

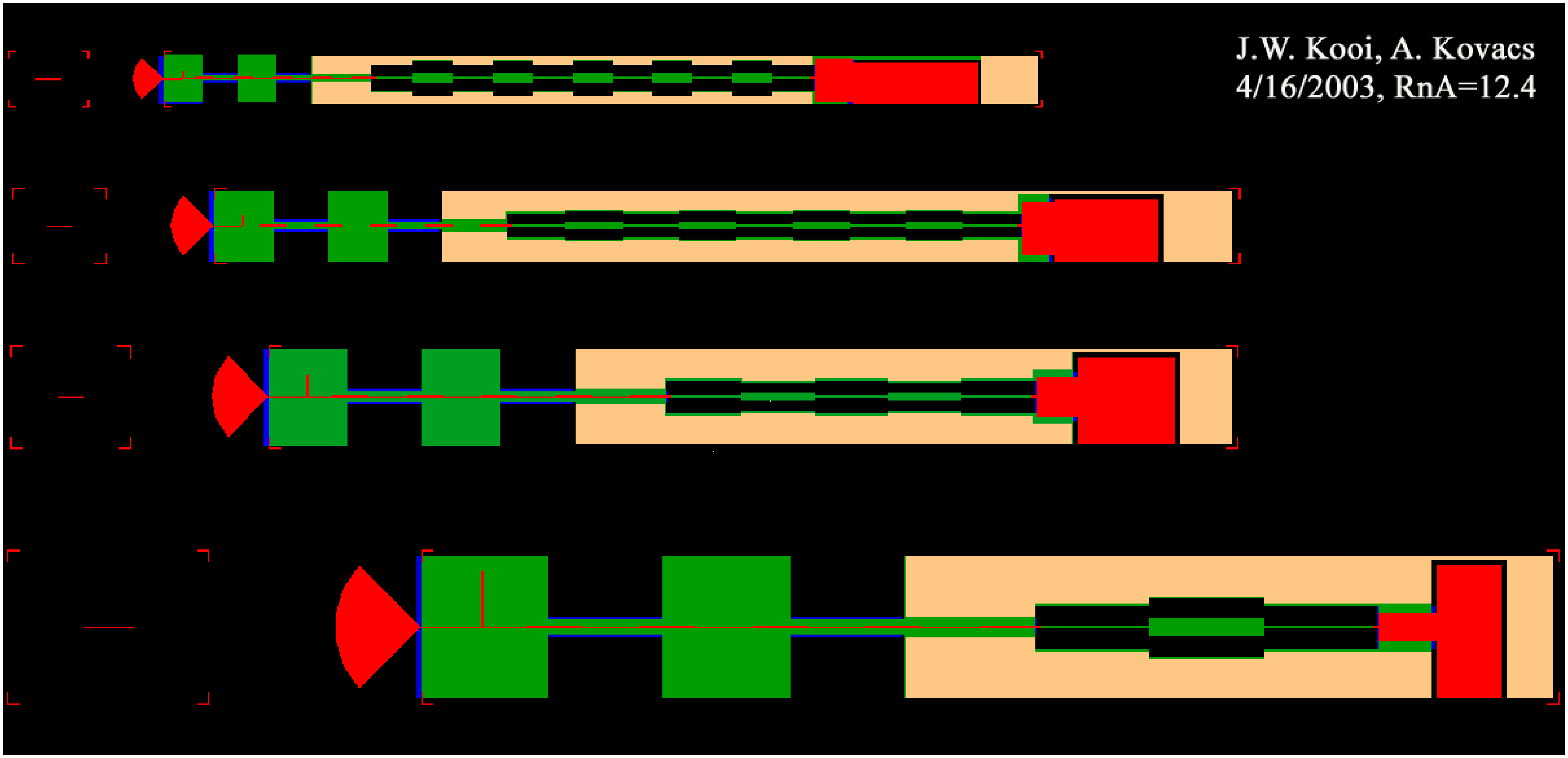
Property	**ΔProperty**	**ΔArea**	**ΔT (K)**
SiO Thickness	15%	11.5%	1.5
εr	5%	1.6%	0.3
ρ⊥	20%	1.4%	0.0
RnA	20%	0.4%	1.0
C_junction	10%	9.7%	0.5
Total		**15.2%**	**3.3**

Table 2. Area mismatch and increase of mixer noise temperature based on typical fabrication tolerances.

Meet The Family...

The new fix-tuned mixer designs for the CSO.

580 – 730 GHz
400 – 540 GHz
280 – 420 GHz
180 – 280 GHz



J.W. Kooi, A. Kovacs
4/16/2003, RnA=12.4

Predicted Receiver Performance

(averaged in a 4-8 GHz IF band)...

Mixer tuned to optimum performance with a necessary stability requirement...

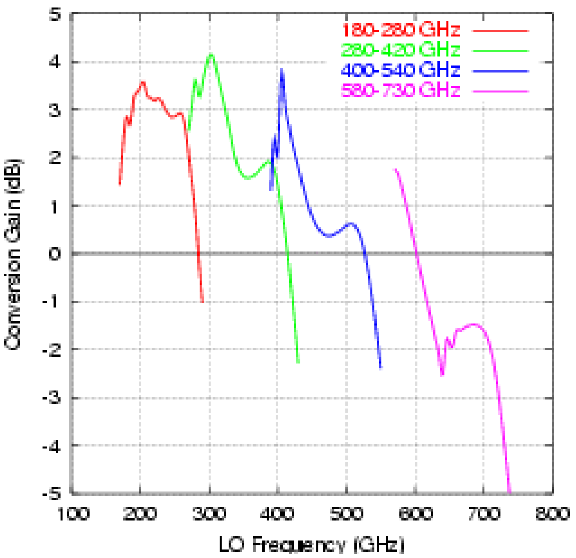


Fig. 1. Mixer Conversion Gain

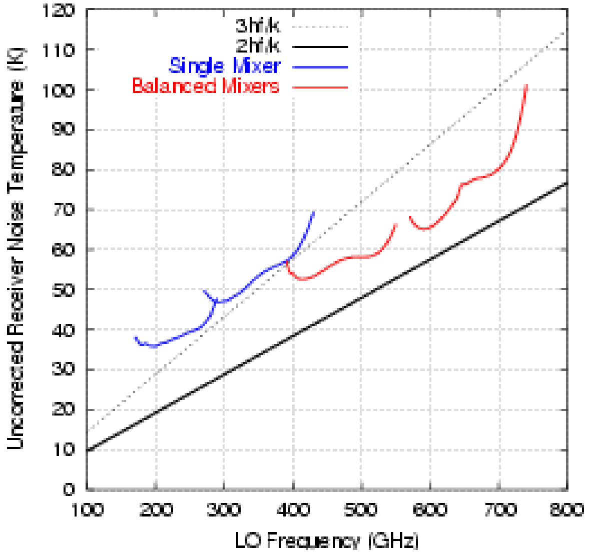


Fig. 2. Receiver Noise Temperatures with simulated optics models for dual frequency receivers. The 470 and 650 GHz bands are implemented in a balanced configuration

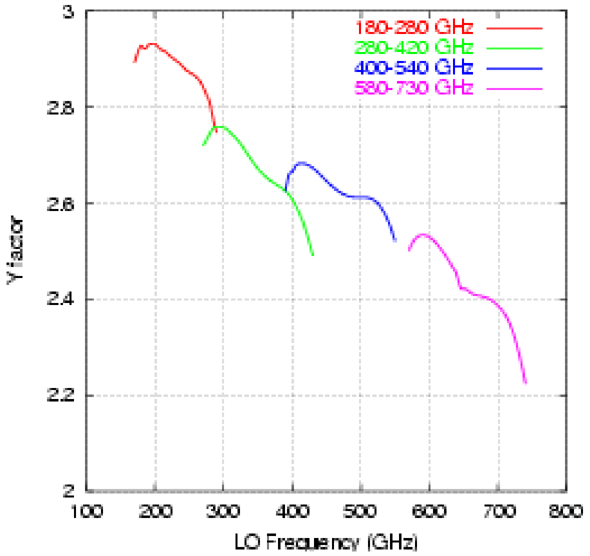


Fig. 3. Predicted Y-factors.

...And the Corresponding Tuning (only the best!)

Reliable & Reproducible Tuning

The power of **SuperMix** manifests itself not only in its capability of optimizing complex structures containing non-linear elements, but also to help find out what operating conditions will provide optimal performance. In the case of our SIS mixer designs, this mainly means determining the optimal combination of bias voltage together with LO pumping power. While incident LO power is difficult to verify, one can use the DC junction current (also predicted by **SuperMix**) as a proxy measure. The values of bias voltage and junction current can then be accurately set by an approporiate tuning electronics, eliminating the dark witchcraft of receiver tuning (though everyone swears by their own method). All this while strictly obeying stability...

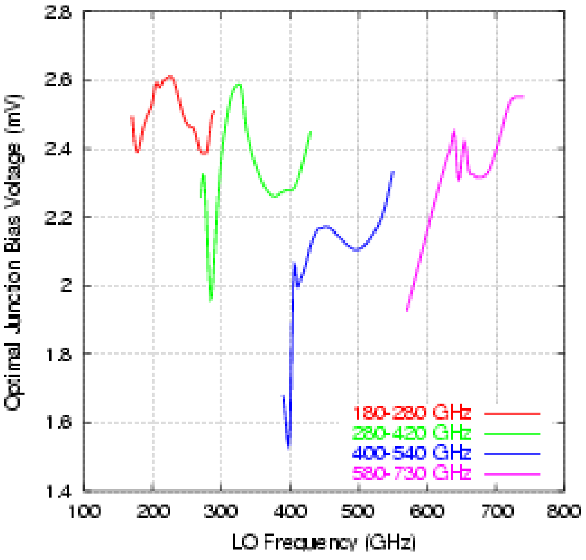


Fig. 1. Optimal Bias Voltage

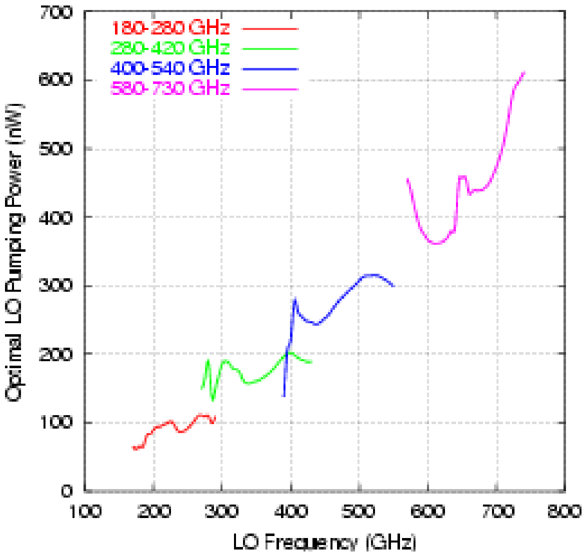


Fig. 2. Optimal LO pumping power

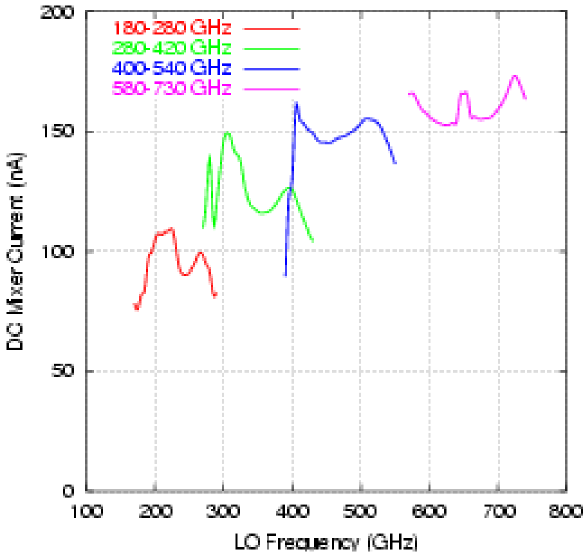


Fig. 3. DC junction current at the optimal tuning

IF throughput

On-chip IF tuning (into 20 Ohms)
Required IF bandwidth 0-9 GHz
6th Order Low-Pass filter beyond 10 GHz
Gain Compression ≅ 1% at 300 K

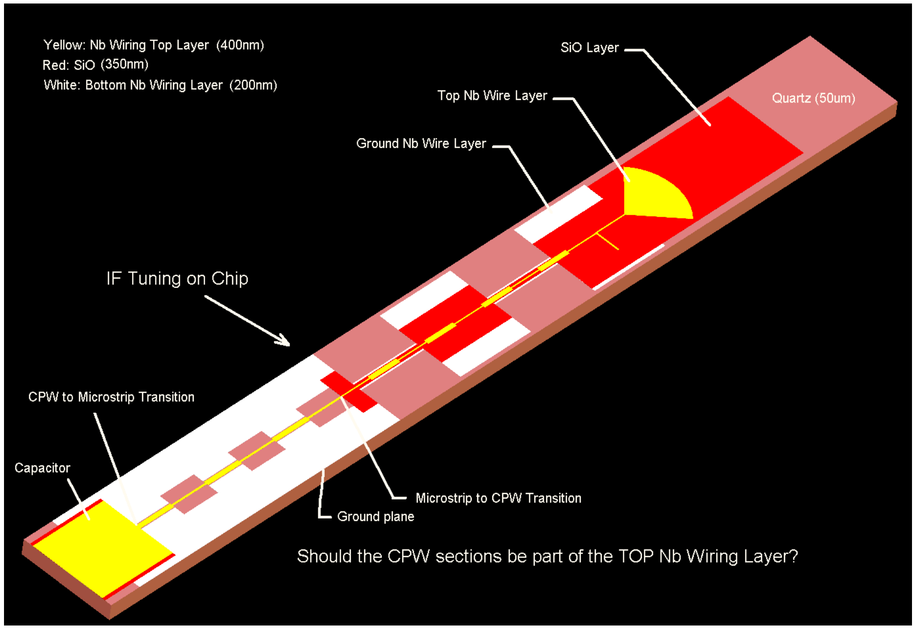


Fig 1. (right) Schematic layout shows the on-chip IF tuning, which essentially consists of a sizeable inductor in the form of a series of quarter wave CPW lines and a large capacitor. Together with the capacitance of the RF tuning components, it essentially constitutes a Π-filter.

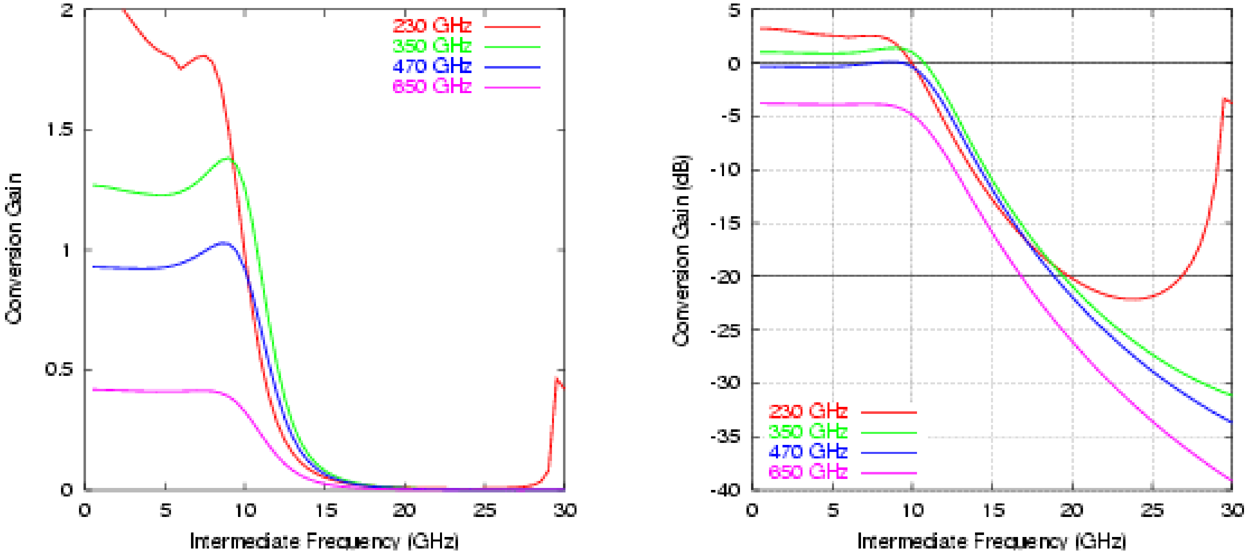


Fig. 2. The IF filter function given 20 Ohms IF termination impedance. The tuning was optimized to provide maximal flatness in the 4-8 GHz band. Plotted are the throughput in direct power gain (left), and in dB units (right). The narrow high-Q resonance seen at the higher frequencies corresponds to resonances on the scale of the entire mixer structure.

Stability

The relatively high RF and IF reflections result not from inadequate power matching but rather are product of the active nature of SIS devices and the interraction between harmonics as a result of non-linear response. Owing to the nearly limitless power sources contained in the pumping LO and DC bias, the power emmitted from the junctions (at the IF and Upper and Lower Side-Bands of various harmonics) can far exceed the incident signal power. With its harmonic balancing capability **SuperMix** is just the tool to predict how much power is reflected into every port.

Reflection constraints may be loosened for improved conversion gain.
Conversely, gain must be sacrificed to achieve stricter constaints on reflections.

This is where we stike the delicate balance (for the 280-420 GHz receiver):

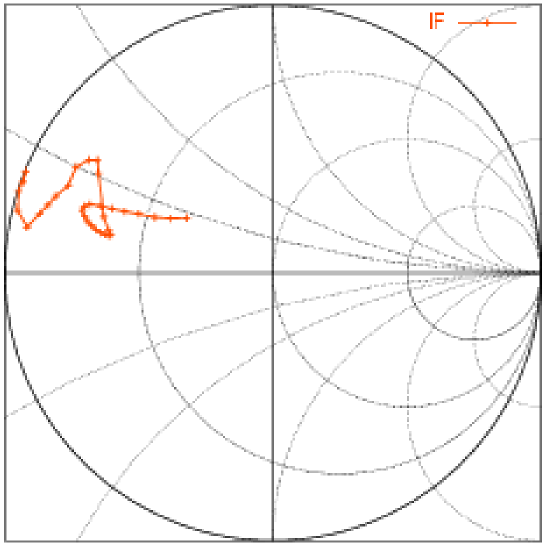


Fig 1. Reflection at the IF port (< 0 dB).
Isolator after the external IF match will prevent resonant noise waves.

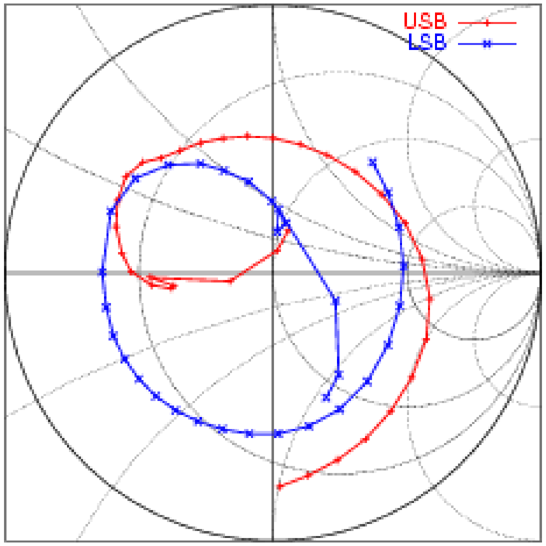


Fig 2. Reflections in the RF. Can constrain more but pay price in gain.

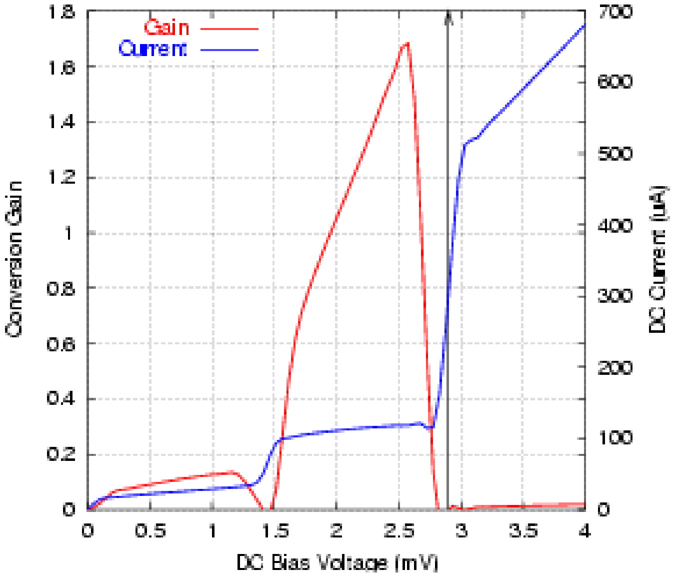
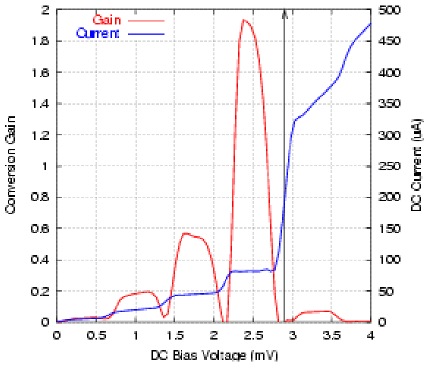


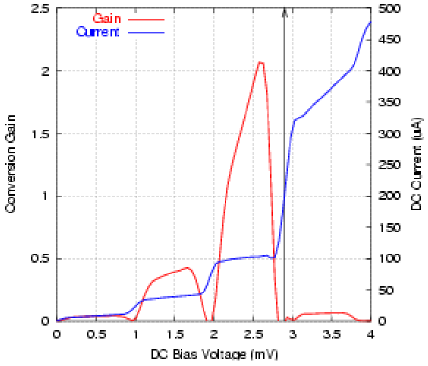
Fig 3. Gain and optimally pumped IV-curve at 350 GHz. Note the positive slope indicating stability

More pumped IV-curves for non-believers

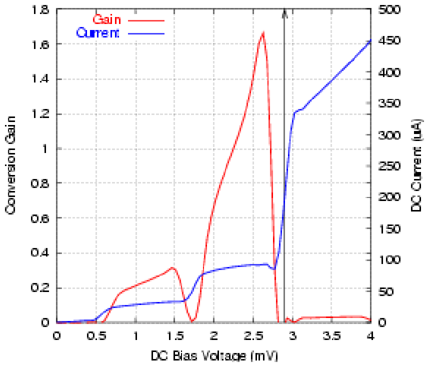
180 -280 GHz



180 GHz

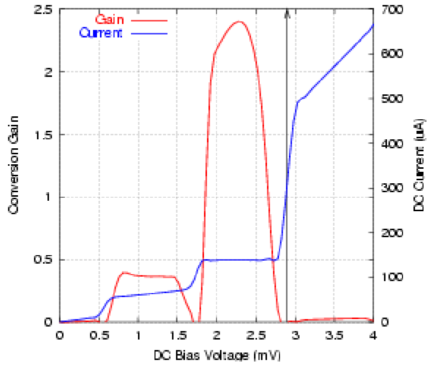


230 GHz

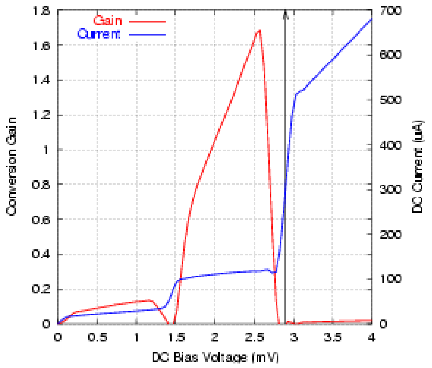


280 GHz

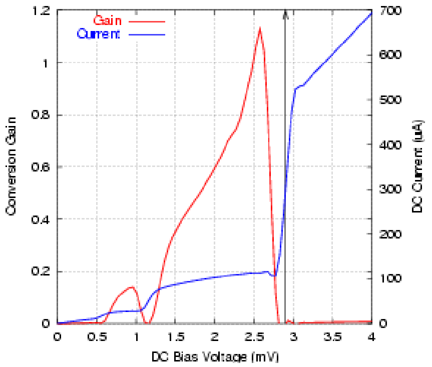
280 – 420 GHz



280 GHz

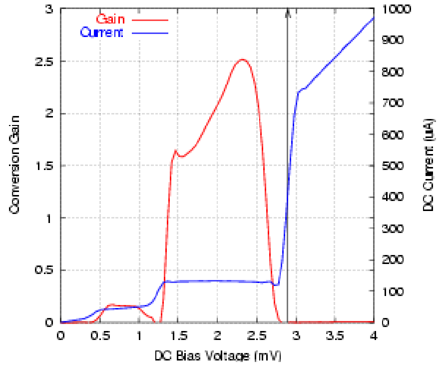


350 GHz

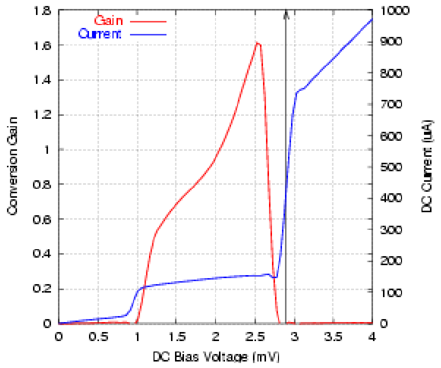


420 GHz

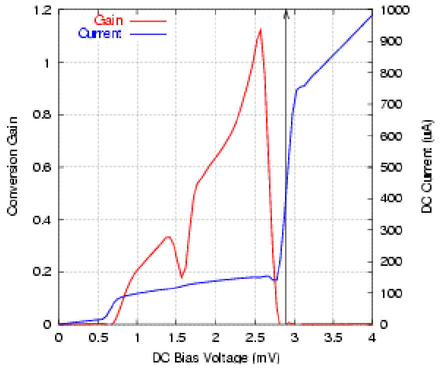
400 - 580 GHz



400 GHz

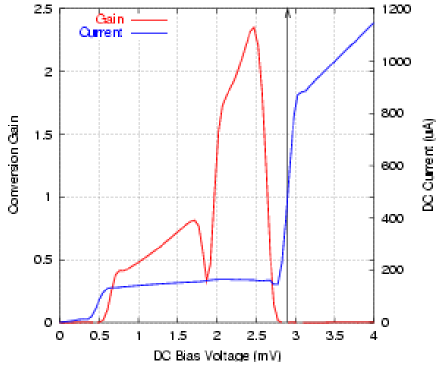


470 GHz

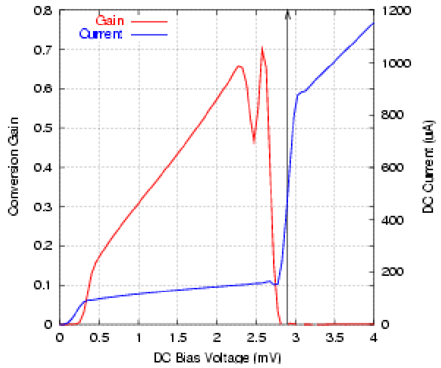


540 GHz

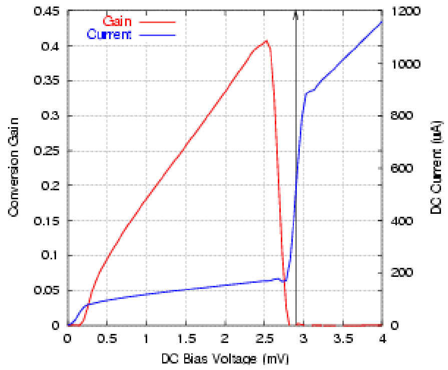
580 - 730 GHz



580 GHz



650 GHz



730 GHz

Designs for 10 and 14 kA/cm^2 Current Densities

Cannot handle the RF bandwidth with low current density?
Just Add More Junctions!!!

2 SIS Junction design is optimal at 14 kA/cm^2 for 100-150 GHz RF band.
2 SIS Junctions at 10 kA/cm^2 handle 100 GHz RF bandwidh optimally.
4 SIS Junctions at 10 kA/cm^2 handle 140-150 GHz RF bandwidth optimally.

Distibuted Junction Arrays have long been advocated to enhance the RF bandwidth beyond the $\Delta\omega \cong 1/RC$ limit. While intuitive models seem to work reasonably well, proper harmonic balancing (all the more crucial for an optimally working design) is quite unthinkable without tools like **SuperMix**. As complexity increases so do the benefits of **SuperMix** design come forward. In our case, the bandwidth requirement for the CSO (ranging 100-150 GHz depending on the band) is such that 4 lower (10kA/cm^2) current density junction handle is just as well (or even better) than twin 14kA/cm^2.

This is important because most fabrication facilities can reliably make 10kA/cm^2 junctions but not easily any higher. Yet, fix-tuned wide-band receivers can be made easily accessible with junction arrays without pushing the current density through the roof...

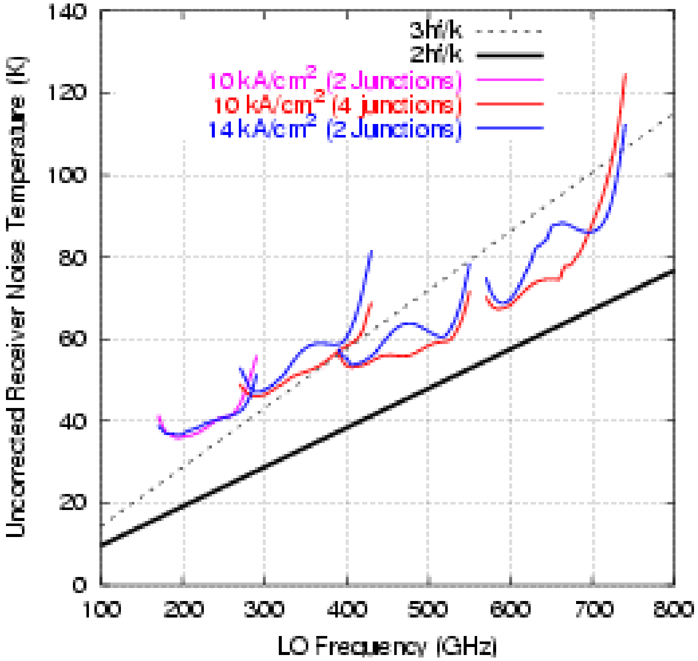


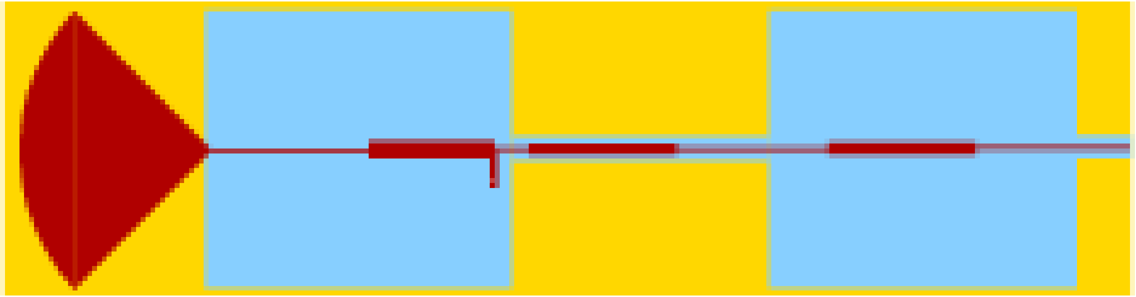
Fig. 1. Predicted Receiver Noise temperatures for the lower and higher current density designs

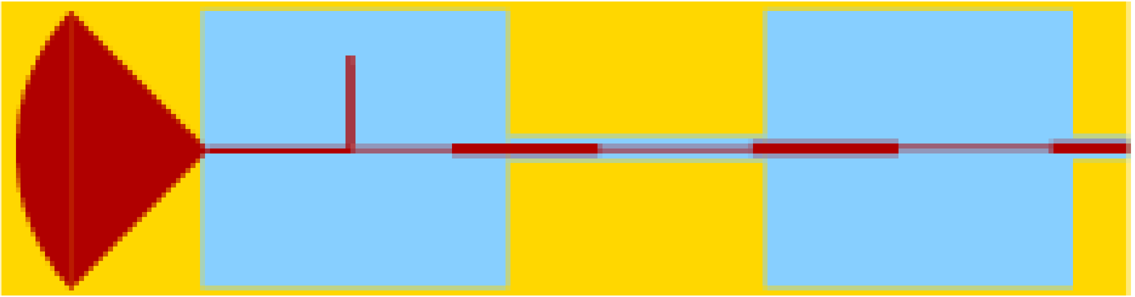
Choosing Among Tuning Structures

SuperMix can quickly evaluate the drawbacks and benefits for various matching networks. (e.g. number of quarter wave transformers to use, inductive lines, hammer filters, symmetric/asymmetric radial stubs, T-junctions, X-junctions etc.)

SuperMix can also help determine the optimum number of juntions in a distributed array, as well as find their dimensions that will provide the best performance.

These designs were found to be ideal for the CSO bands, based on a comparison among dozens of different RF tuning structures. The best single juntion desing is to the right, while below is the best twin junction desing as were found from the sample of desings. Is there one yet superior?...





If you think you have a killer design, you could optimize it and check how well it performs within minutes using **SuperMix**. (Much faster than building and measuring one).

Introduction to **SuperMix**

a non-linear circuit simulator. http://www.submm.caltech.edu/supermix

SuperMix is a set **C++** library routines written at **Caltech** by **J. Zmuidzinas**, **J.S. Ward**, and **F. Rice**. **C++** means it **fast**, and **versatile**, **extensible** and easily **adaptable** to any environment with a bit of coding effort.

```
Microstrip msa, ms1;
open_term opena, openb;
branch T1, T2;
capacitor bondpad, CT;
circuit RFmatch;

...

msa.substrate = SiO;
msa.superstrate = air;
msa.sub_thick = 0.400 * Micron;
msa.length = ef.vary(0.0, 14.5, 100.0, Micron);
msa.width = 4.0 * Micronl

...

RFmatch.connect(choke_section[sections-1], 2, cpwHI, 1);
RFmatch.connect(cpwHI, 2, prepad, 1);
RFmatch.connect(prepad, 2, bondpad, 1);

RFmatch.add_port(ms1, 1);                          // towards the antenna
RFmatch.add_port(bondpad, 2);                      // to the IF output
RFmatch.add_port(T1, 3);                           // towards the SIS1
```

Frequency domain (fast!) analysis of **linear and non-linear circuit elements** (n-ports), which are connected through circuit nodes. It is NOT a E-M simulator!

Its primary purpose is greatly enhancing SIS design, by combining all necessary tools within a single package. Common **circuit elements**, **signal propagation and noise analysis** and **harmonic balancing** are combined with powerful **optimizers**. (Similar tools exist, albeit separately with much time and effort going into interfacing between them.)

Optimization can be performed over complex criteria which can be easily composed of readily supplied terms (such as noise targets, S-matrix matches, gain targets and limits) and custom terms

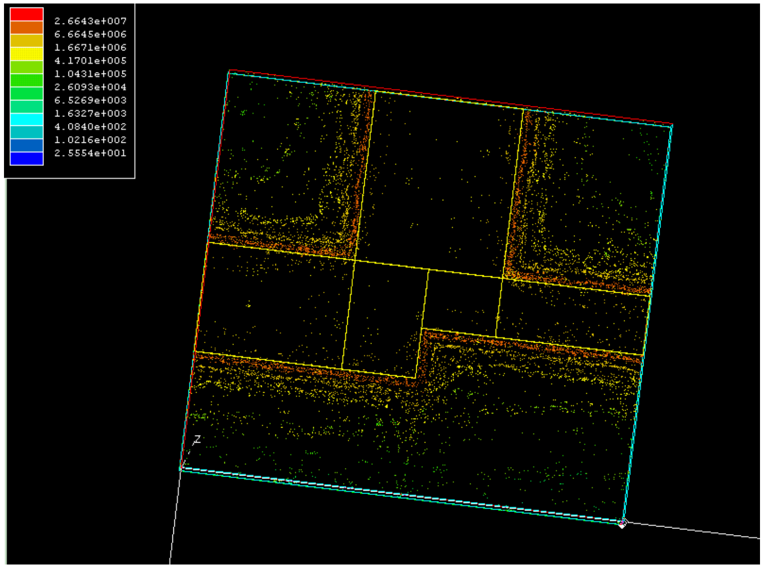
Enhancing the **SuperMix** Model

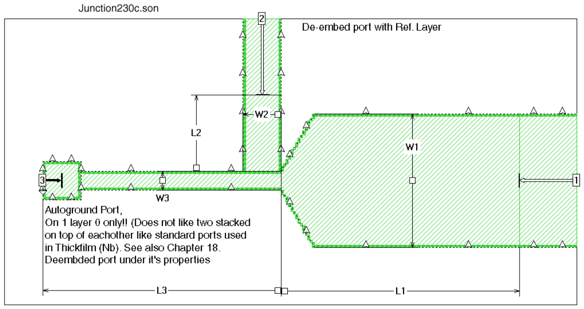
Since **SuperMix** is not an E-M simulatior is does not easily deal with structures with comples surface currents. However, with some external help it manages just fine... How?

Step 1. Model the critical structure in an appropriate E-M simulator (HFSS, Sonnet).

Step 2. Fit the resulting S-parameter file with an appropriately chosen **SuperMix** model by optimizing correction terms.

Step 3. Apply the determined correction terms for consequent **SuperMix** analysis.





Autoground Port,
On 1 layer 0 only!! (Does not like two stacked on top of eachother like standard ports used in Thickfilm (Nb). See also Chapter 18.
Deembded port under it's properties

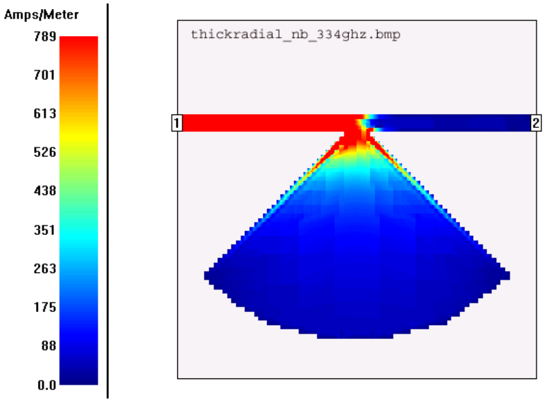
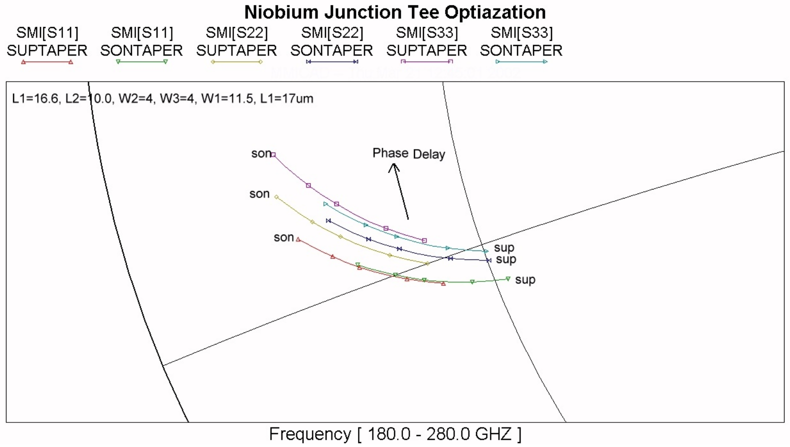
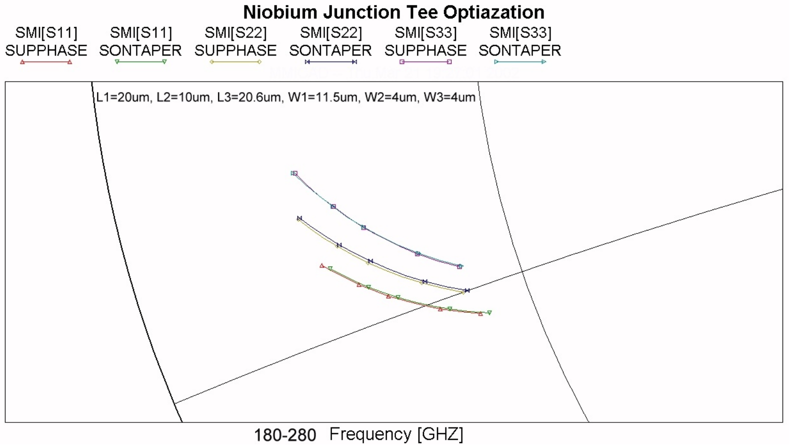
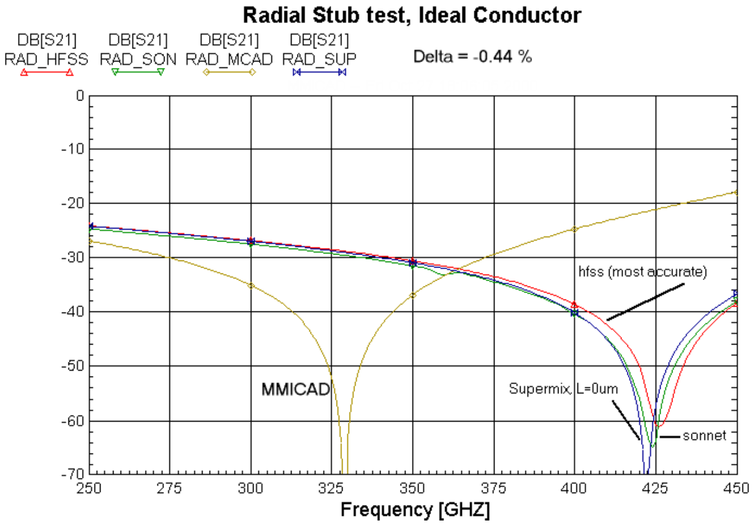


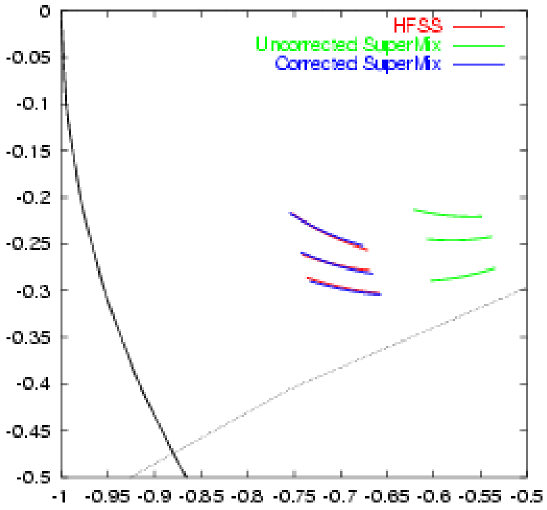
Fig. 1. Examples of Structures analysed the above described way.

Enhancing the **SuperMix** Model (Part 2)









Examples of Determining and Applying corrections to the **SuperMix** Model. (top left) Clear disagreement between the **SuperMix** model for a tapered T-junction and the Sonnet simulation, highlighting the limitations of **SuperMix** to simulate complex surface currents. However, applying an optimal set of length corrections makes the match nearly perfect (top right). Another example is the successful determination of the radial stub neck length in the **SuperMix** model to bring it to agreement with Sonnett and HFSS (bottom left). Finally, an actual tuning structure in the CSO 650GHz receiver design. The Tee model has been modified by an added capacitance as well as corrected lengths (bottom right).