

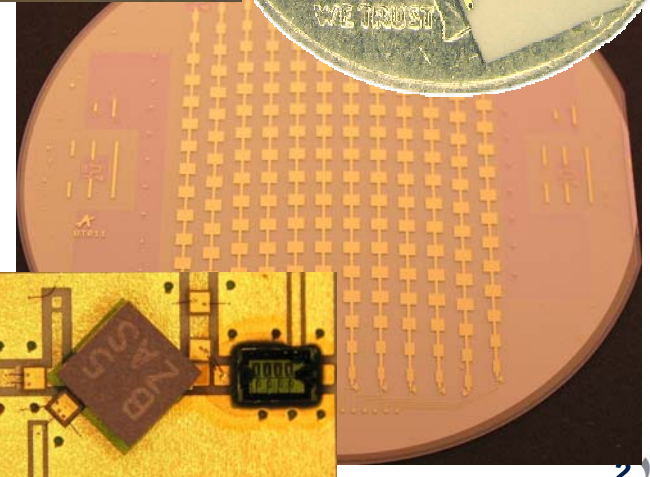
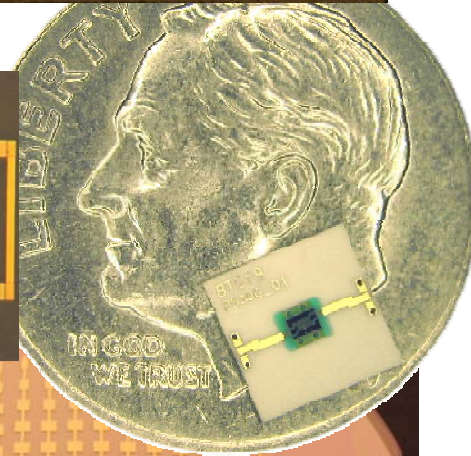
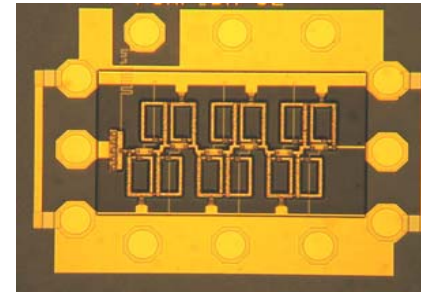
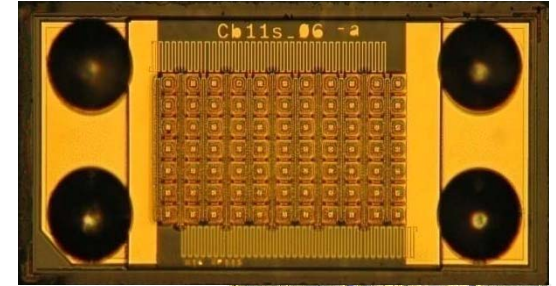
## *BaSrTiO<sub>3</sub>-Based 30-88MHz Tunable Filter*

**Dr. Ken Zhang and Prof. Robert York**



# Company Overview

- **Founded in 1999**
- **Privately held company in the Santa Barbara area**
- **Specializing in tunable RF and microwave components for the analog RF front end:**
  - **Analog Phase shifters from 800 MHz to 50 GHz**
    - Electronically scanned antennas
    - Amplifier linearization
  - **Tunable matching networks**
    - Antennas and amplifiers
  - **Tunable filters**
- **Semi-fabless operation**
  - **Material & process development in house**
    - Thin film tunable dielectrics
  - **RF circuit design and testing in house**
  - **All other front- and back-end processes outsourced**

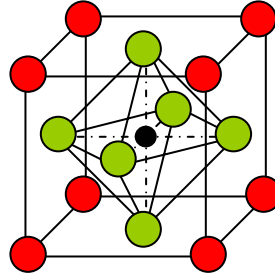


## *Agile BST Technology*



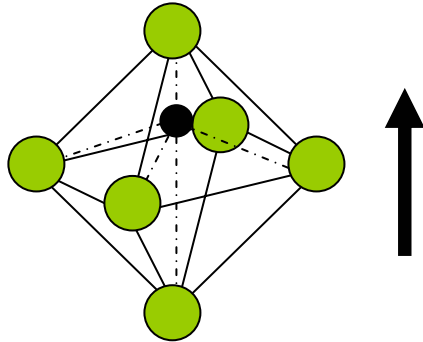
# Ferroelectric vs. Paraelectric

- Barium, Strontium
- Oxygen
- Titanium



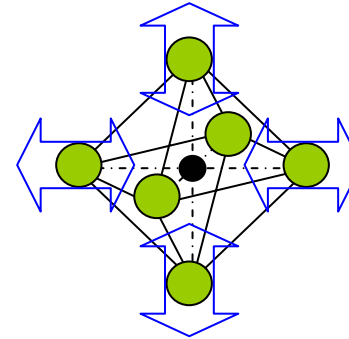
BST is a Perovskite Oxide structure and shares Ba, Sr and O with adjacent structures

## Ferroelectric Behavior



Titanium atom displaces in the lattice causing ferroelectricity  
 $T > T_c$ : (paraelectric phase) very high dielectric constants (compact capacitors),

## Paraelectric Behavior

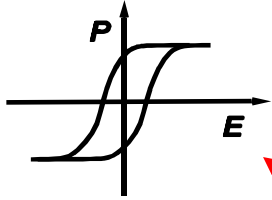


Titanium atom remains centered in the lattice due to restoring forces causing the structure to stiffen  
 $T < T_c$ : (ferroelectric phase) hysteretic polarization-field response (memories)

*In both cases with applied voltage the dielectric constant changes which changes the materials capacitance*

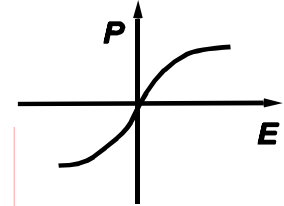
# Thin-Film vs. Bulk BST

## Ferroelectric Behavior

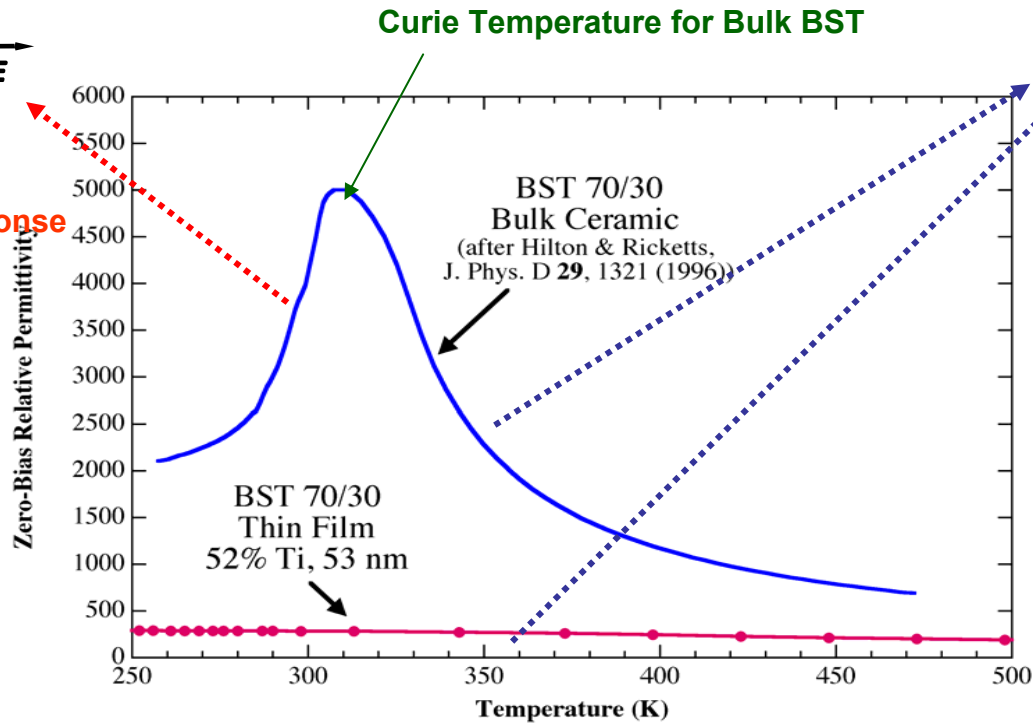


## Hysteretic Response

## Paraelectric Behavior



## Non-Hysteretic Response



## Thin-Film properties differ markedly from those of bulk BST

Efforts with Barium Strontium Titanate (BST) by CVD and sputtering showed:

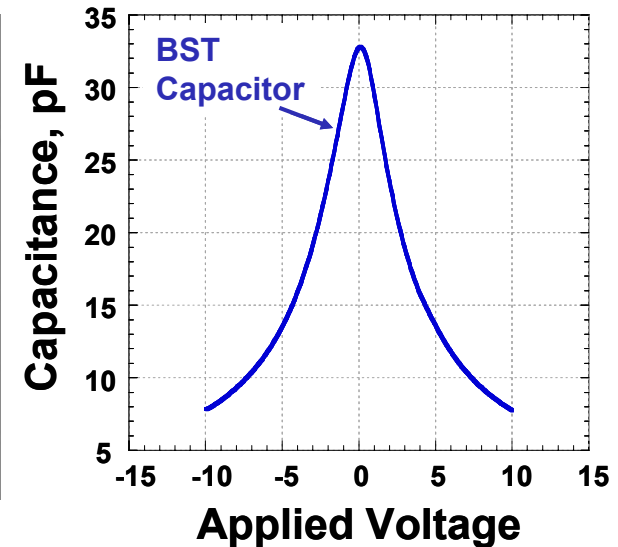
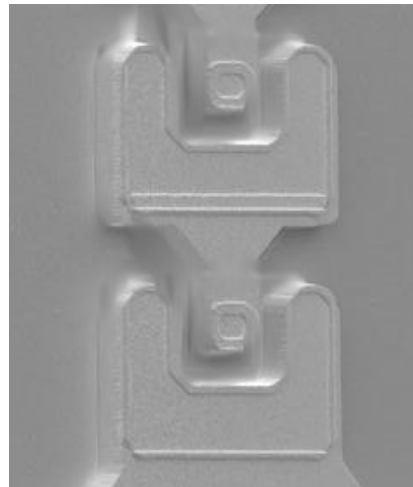
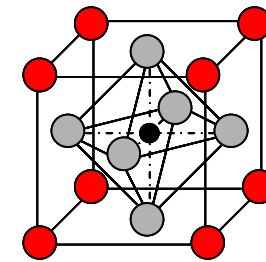
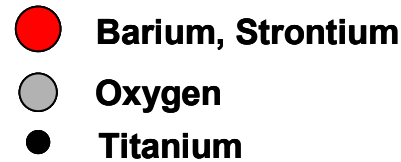
**strongly field-dependent permittivity; low temperature coefficients; good high-frequency response**

# Agile's BST Technology

## Thin-Film BST:

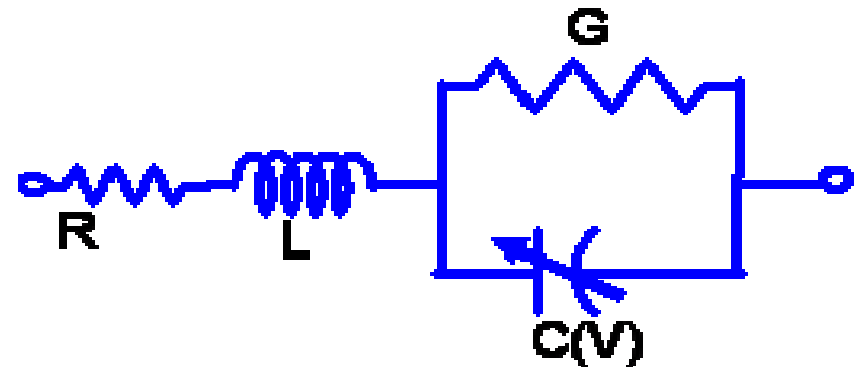
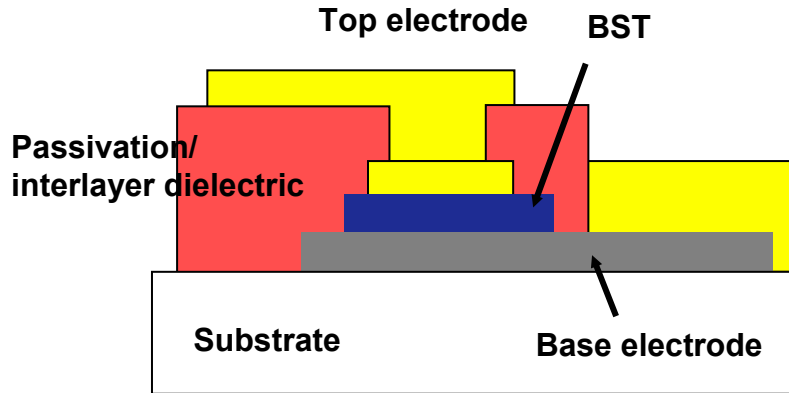
- Voltage Variable Dielectric
- High capacitance density (10-50 nF/mm<sup>2</sup>)
- Wide Range of Control Voltages (< 3 Volts to >20V)
- Useable Tunability of 2:1 or more
- No diode-conduction: operates at zero bias with large AC swings
- Integration on insulating substrates with other high-quality passives
- Excellent Linearity
- High power handling
- Good temperature stability
- No hysteresis
- Good Q at operating frequencies
- Essentially zero power draw with very low leakage currents

## Barium Strontium Titanate



general tuning curve

# Agile BST Capacitor Model



*This model consists of resistive and reactive elements and a BST voltage-dependent capacitive element.*

*Linked to layout software and artwork macros for foundry design palette*

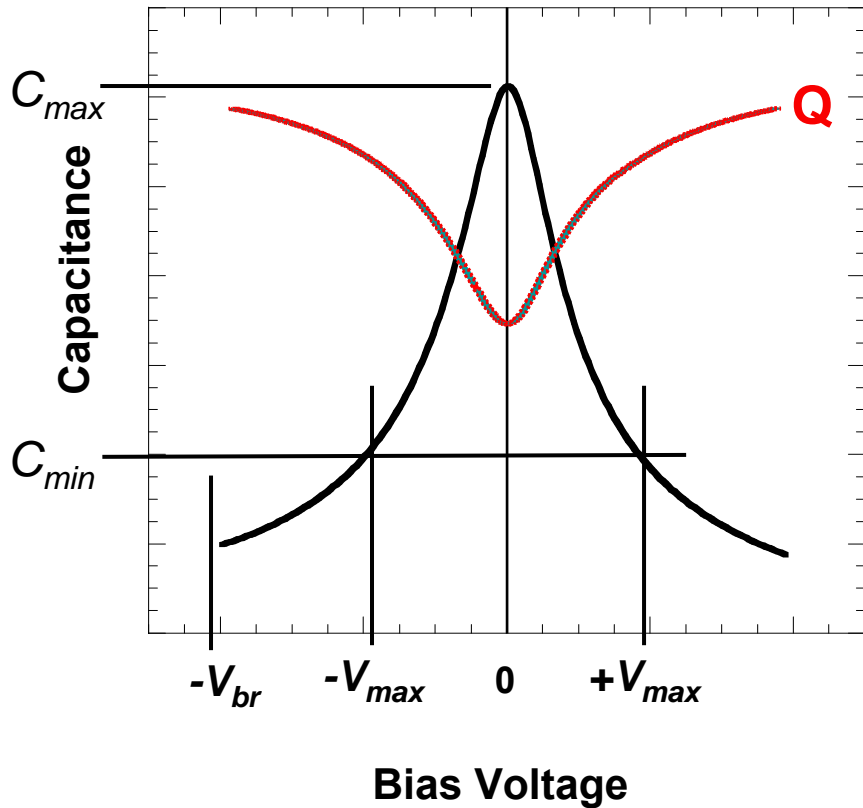
$$f_c = 1 / ( 2 \pi RC )$$

$$f_{res} = \frac{1}{2 \pi \sqrt{LC}}$$

$$Q_{film} = 1 / (\tan \delta )$$

**Agile BST Capacitor equivalent circuit**

# BST Varactor C-V Model



## CV curve model

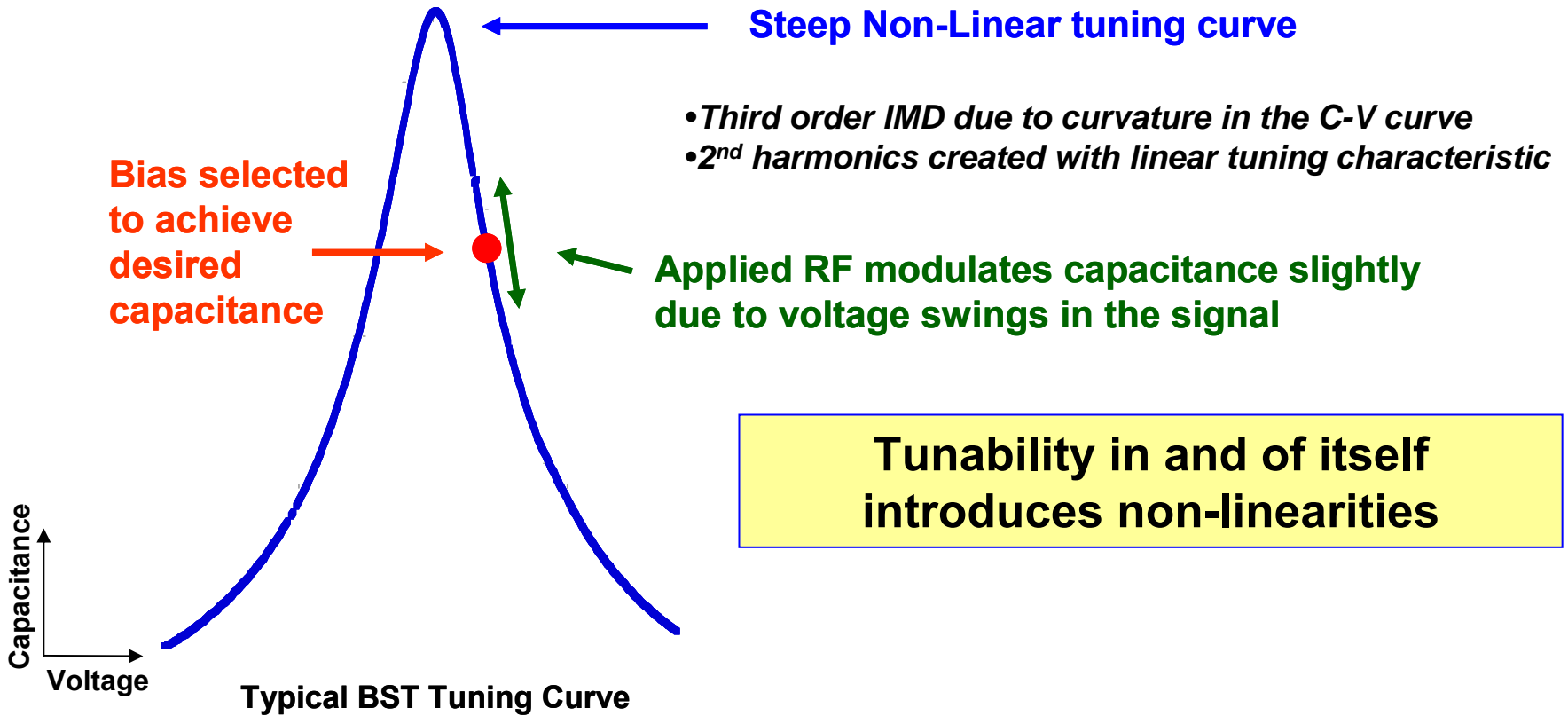
$$C(V) = \frac{C_{max}}{2 \cosh \left[ \frac{2}{3} \sinh^{-1} \left( \frac{2V}{V_2} \right) \right] - 1}$$

## Total Q-factor of the BST device in terms of loss components

$$\frac{1}{Q_{total}} = \frac{1}{Q_{leakage}} + \frac{1}{Q_{BST}} + \frac{1}{Q_{Pt}}$$

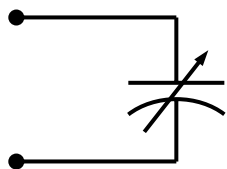
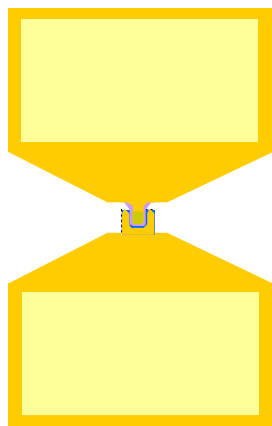
*BST varactors allow for larger AC swings at low voltages  
Higher Q at operating frequencies*

# BST Non-Linearity Analysis

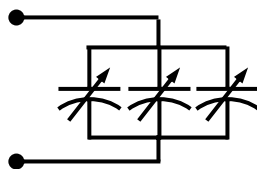
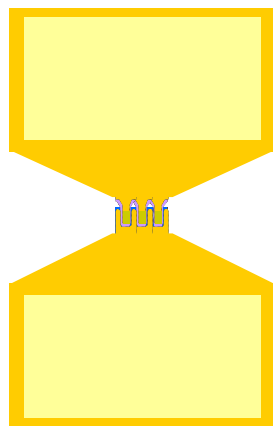


***What can be done to improve this problem?***

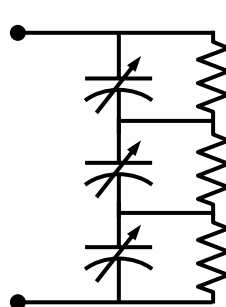
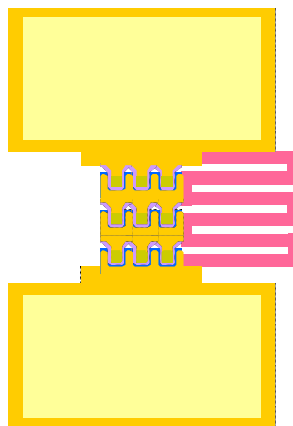
# Stacked Capacitor Concept **AGILE** RF



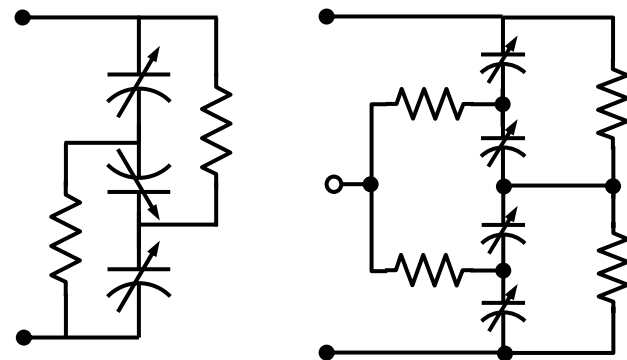
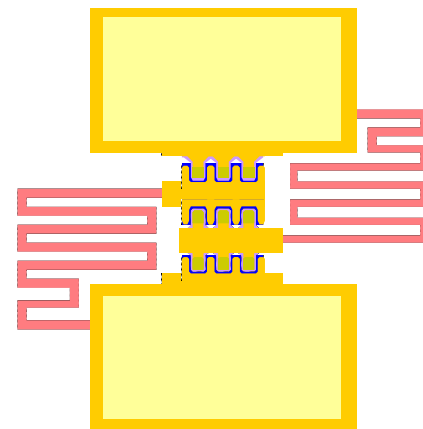
Single Capacitor



- High current handling
- Low metal loss



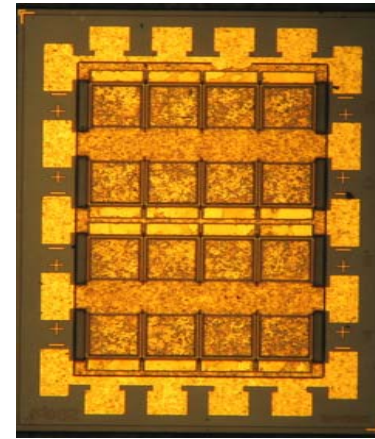
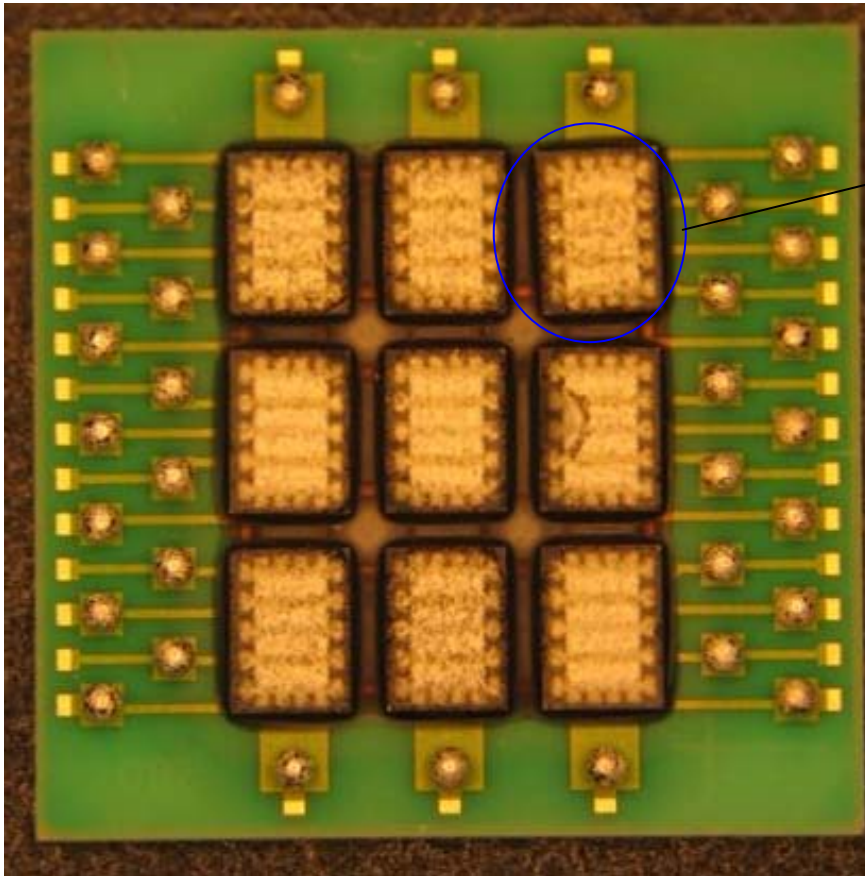
- High breakdown voltage
- High RF power handling
- High control voltage



*Patent US 6,674,321*

- High RF voltage handling
- Low control voltage

# 12x12 Stacking Capacitor Array

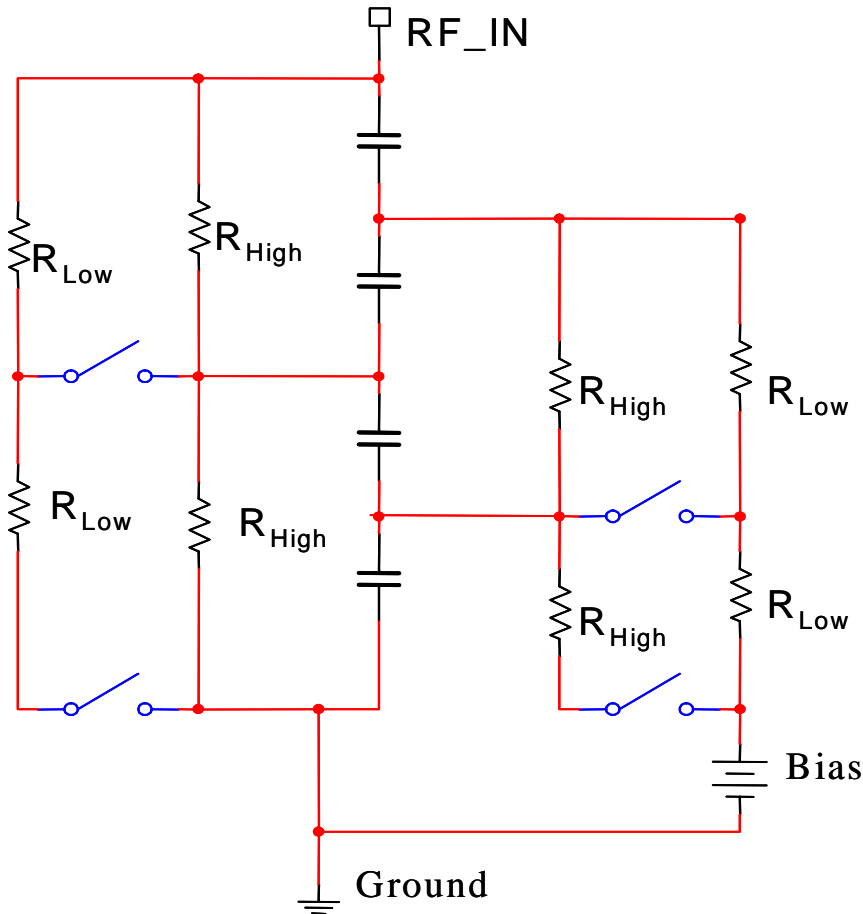


4x4 Capacitor Array Die

- **Advantage**
  - High Power handling: over 30dBm
  - Capacitor array IIP3 is over 65dBm
  - Smaller than 5% temperature variation at all bias voltage
- **Disadvantage**
  - Large value resistor are used to maintain Q value, capacitor switching time become longer

12x12 Capacitor Array in Carry

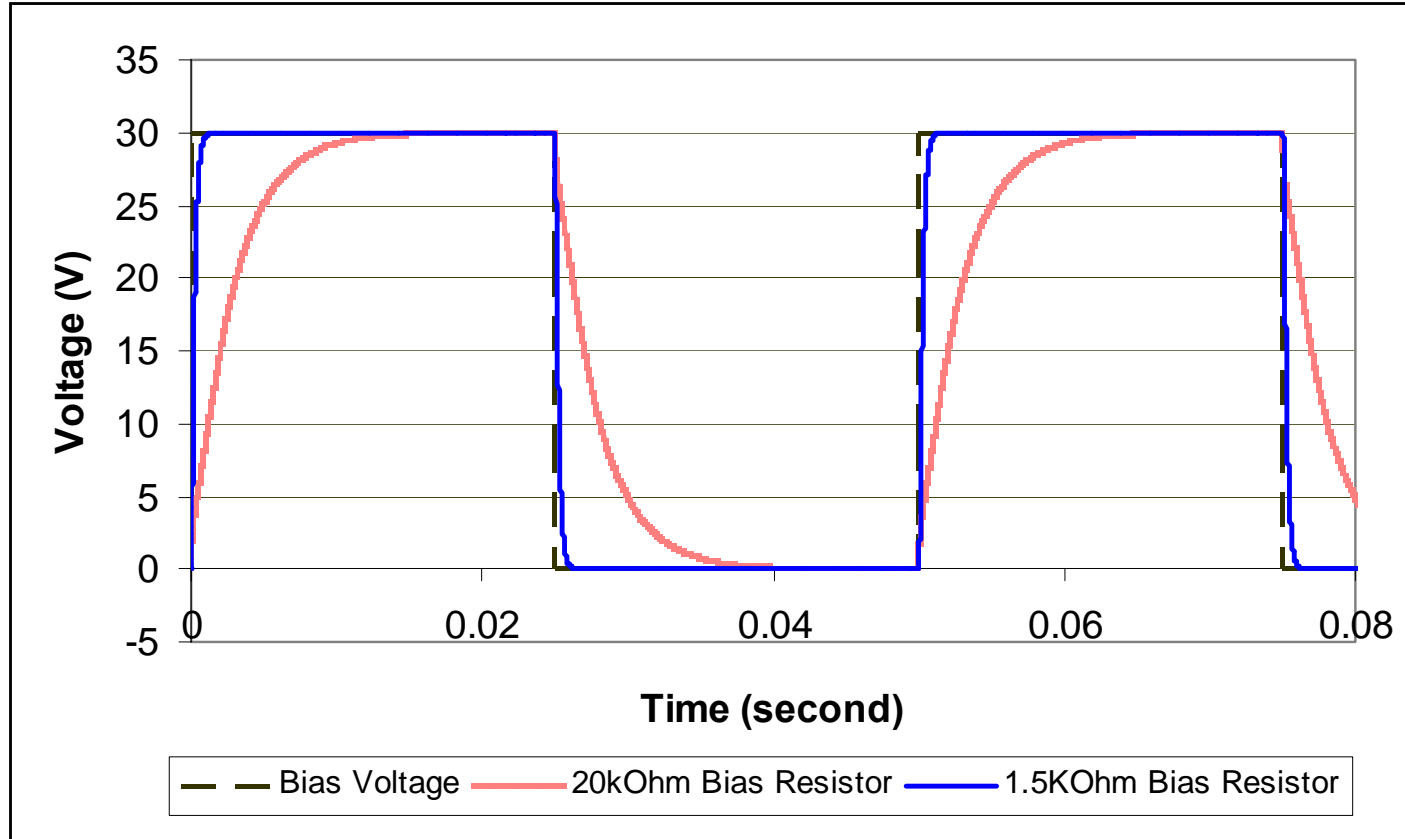
# Switching Speed Analysis



Each RF blocking element consist of two shunt resistor: one is large, another is small. RF switch is linked between the two resistors. The switches will be closed during frequency tuning to speed up DC voltage transition time.

**Circuit diagram of capacitive element**

# Comparison the Transition Time with Different Resistors

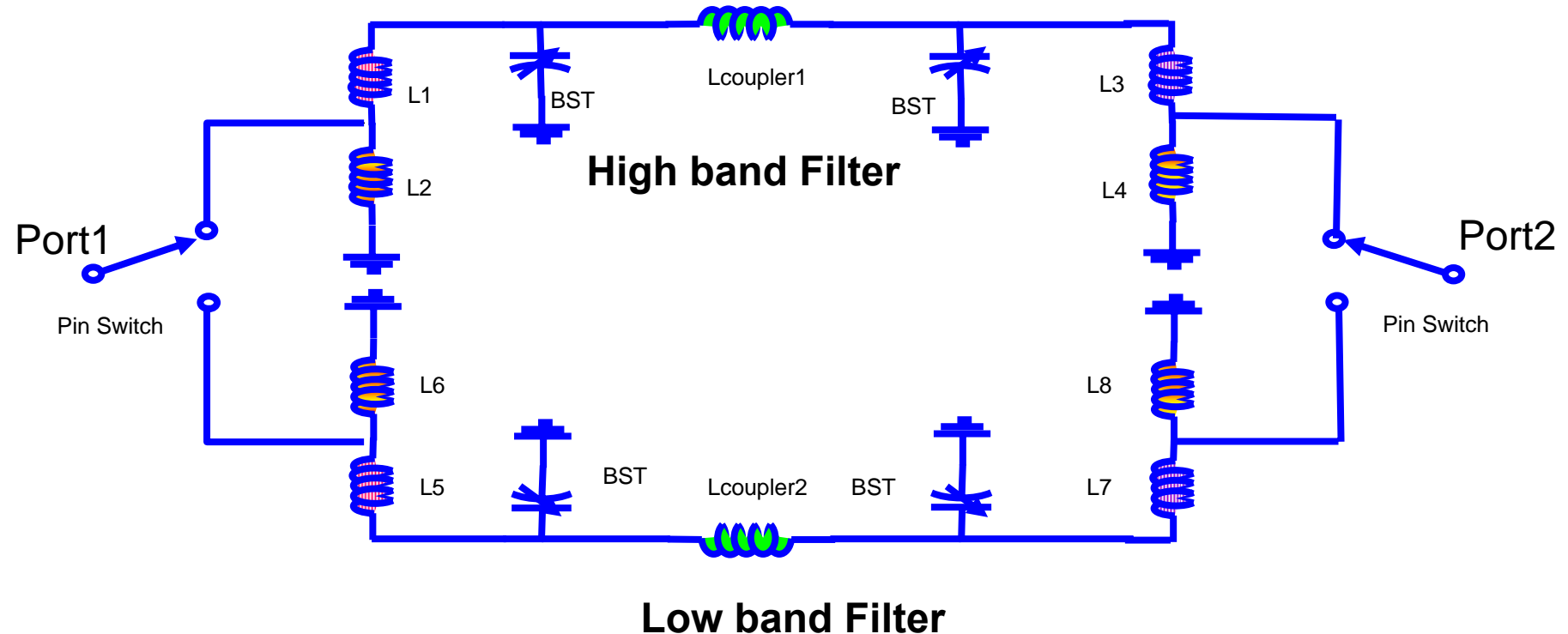


**The tuning speed will be improved from  $>6.0\text{ms}$  to  $<450\mu\text{s}$ , while the bias resistors in the low band change from  $20\text{k}\Omega$  to  $1.5\text{k}\Omega$ .**

## *Tunable Filter Design and Testing*

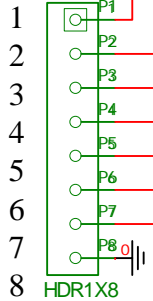
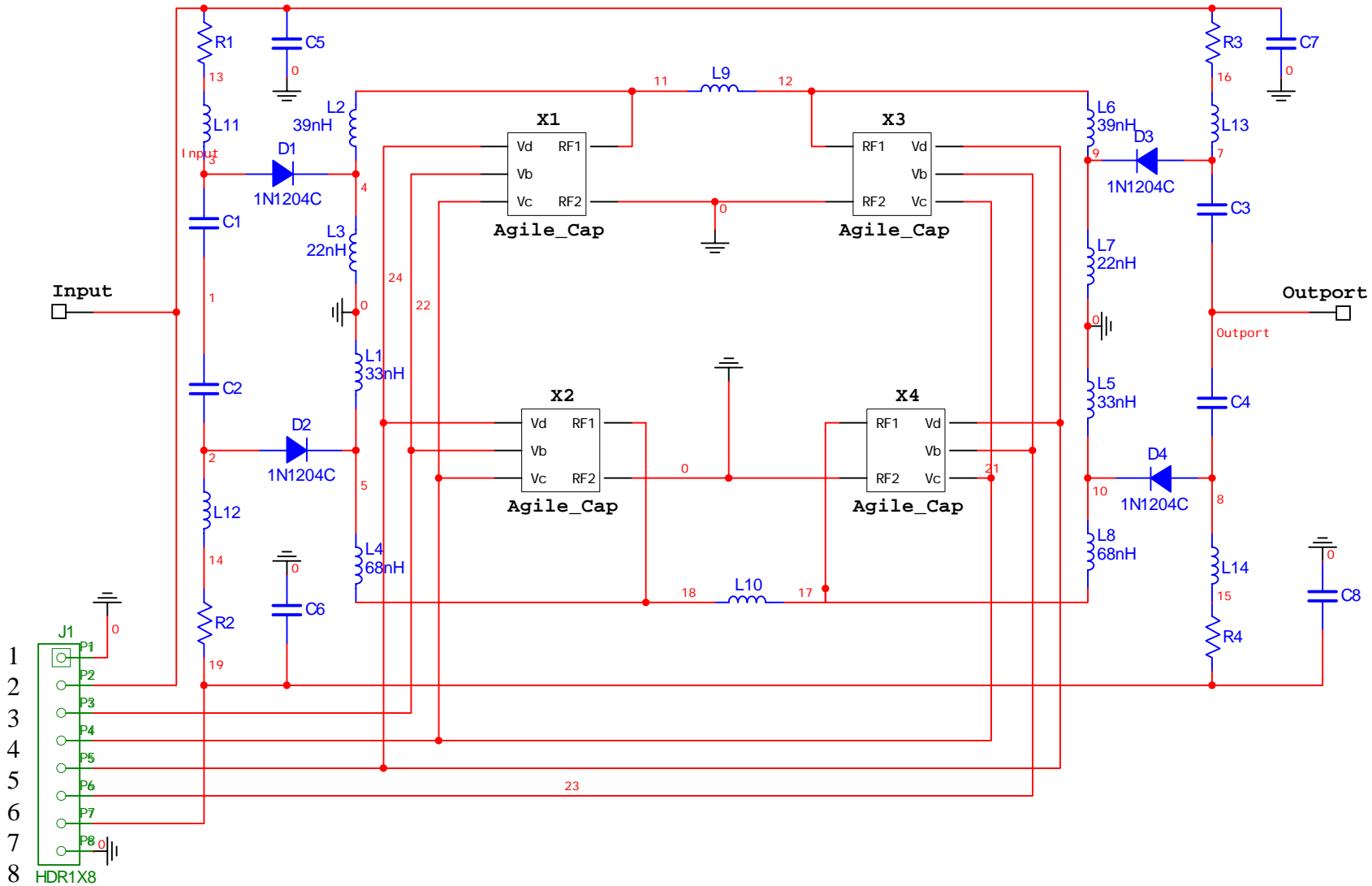


# General Two Tunable Filter Schematic

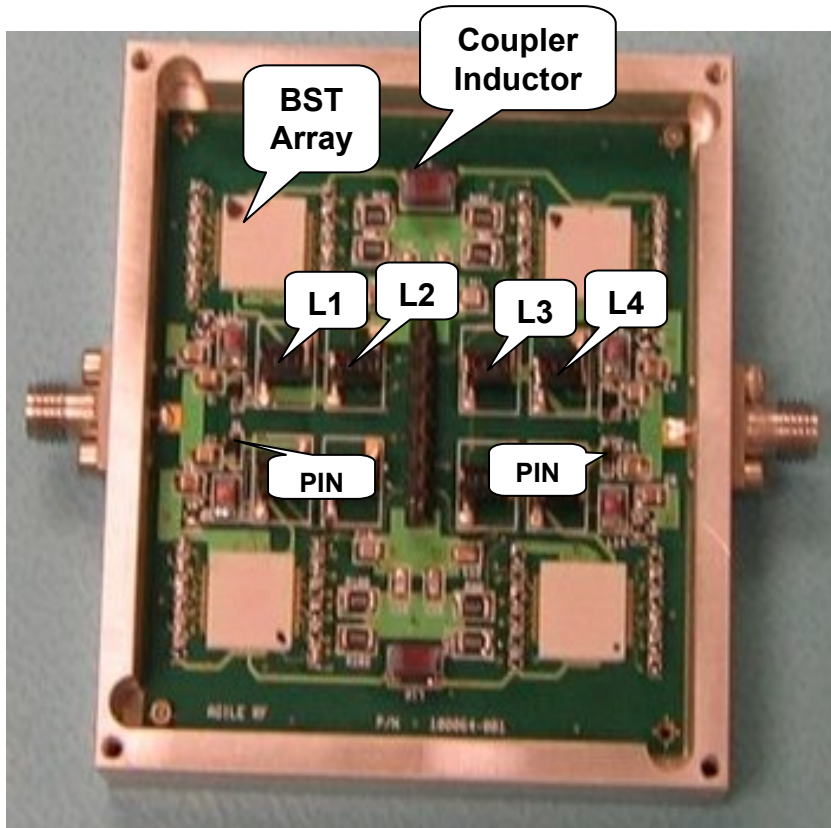


Two tunable bandpass filters have been design to cover 30-88MHz: low Band (30-50 MHz) and high Band (50-88 MHz). High performance PIN diodes are used to select the operation bands.

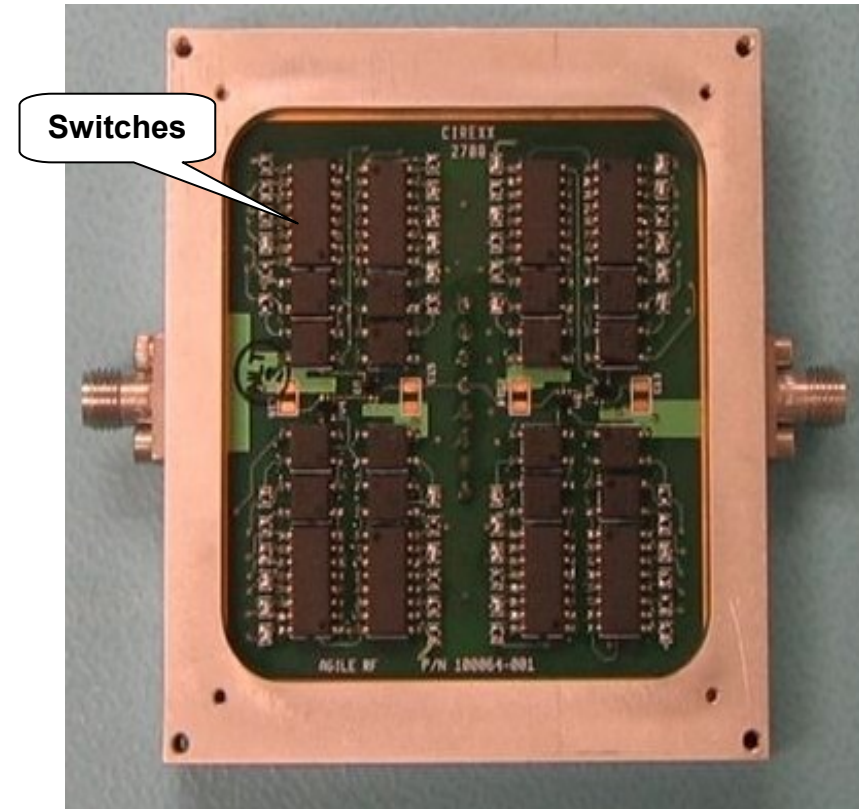
# Schematic Of Two-Band Filters



# Assembled Filter

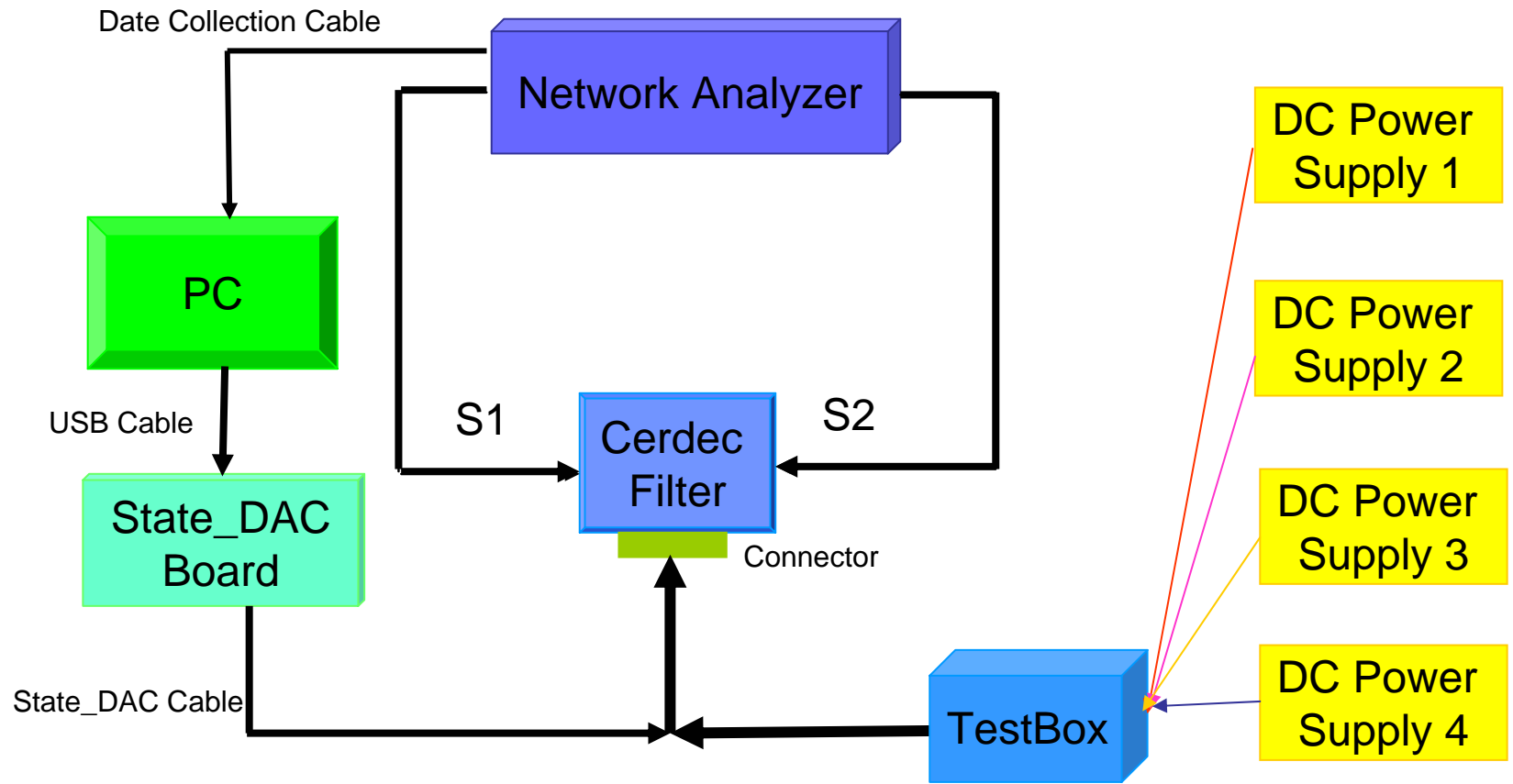


Top View

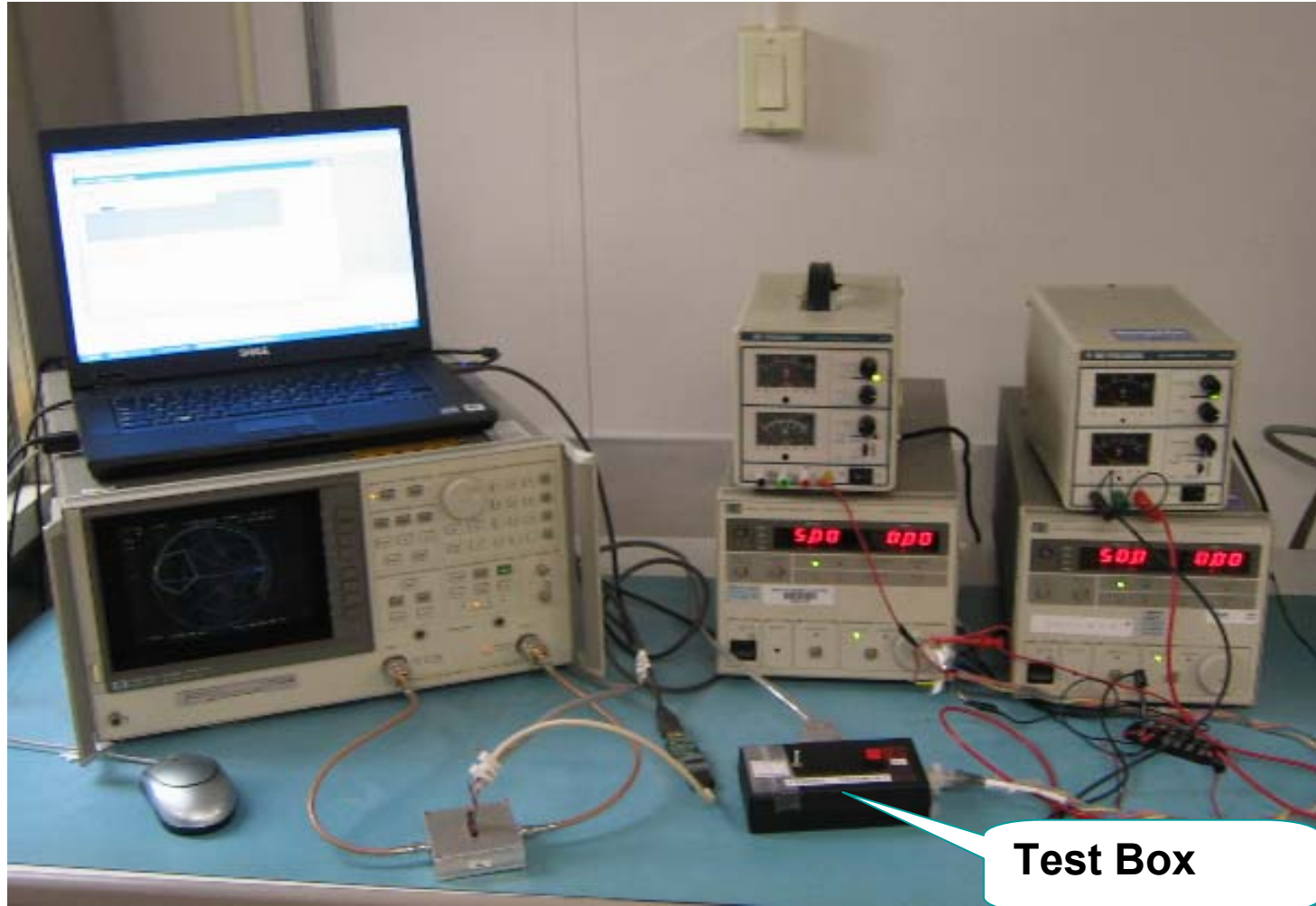


Bottom View

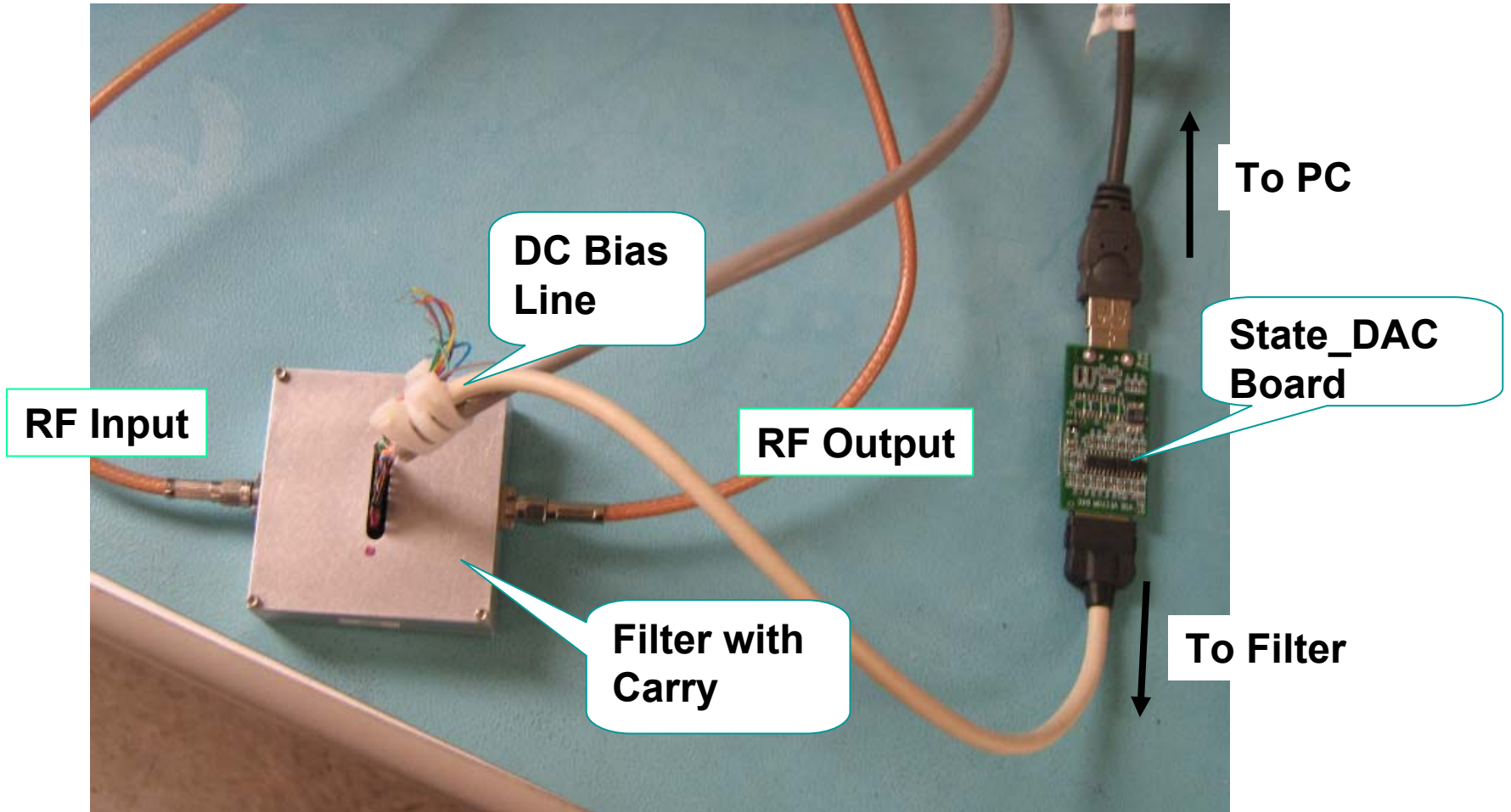
# Tunable BPF State-DAC Testing Set-up



# Cerdec State-DAC Test set-up



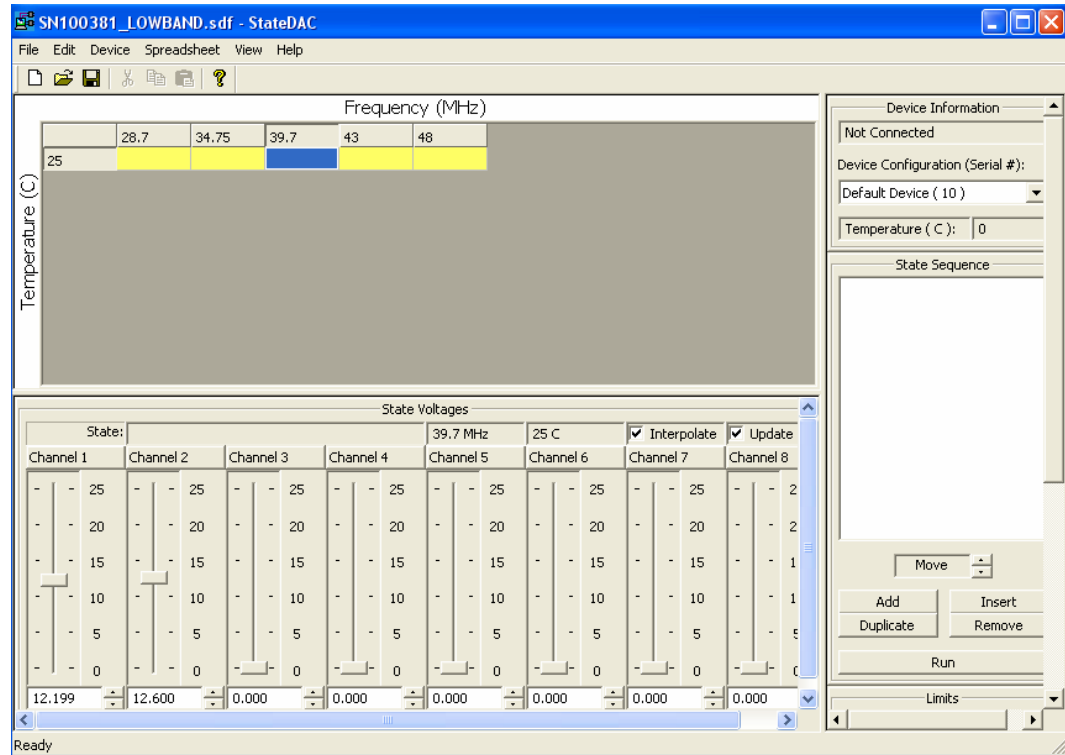
# Zoom: Cerdec State-DAC Test set-up



# State\_DAC Control Board



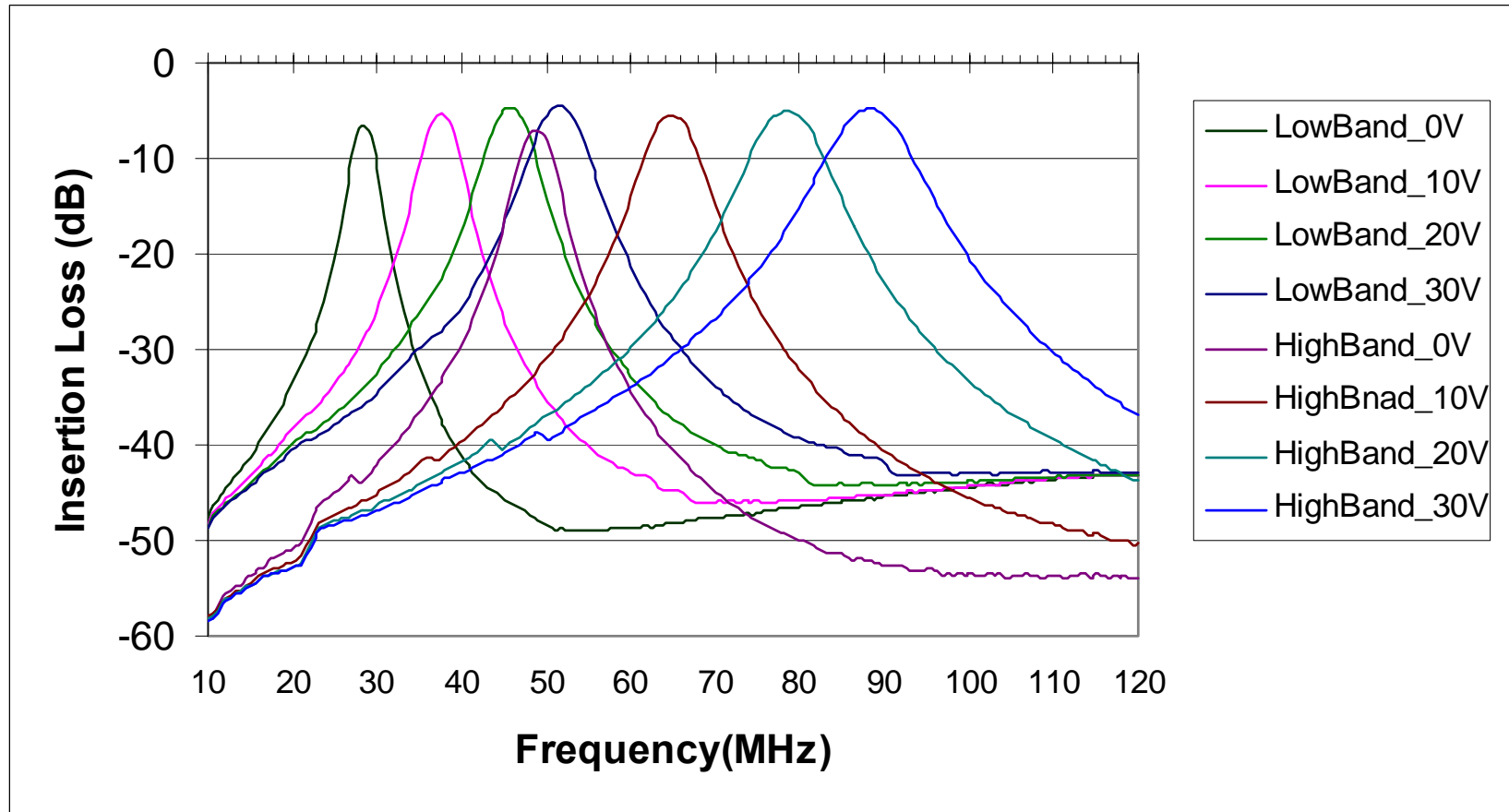
**State\_DAC Board**



**DAC Control Window**

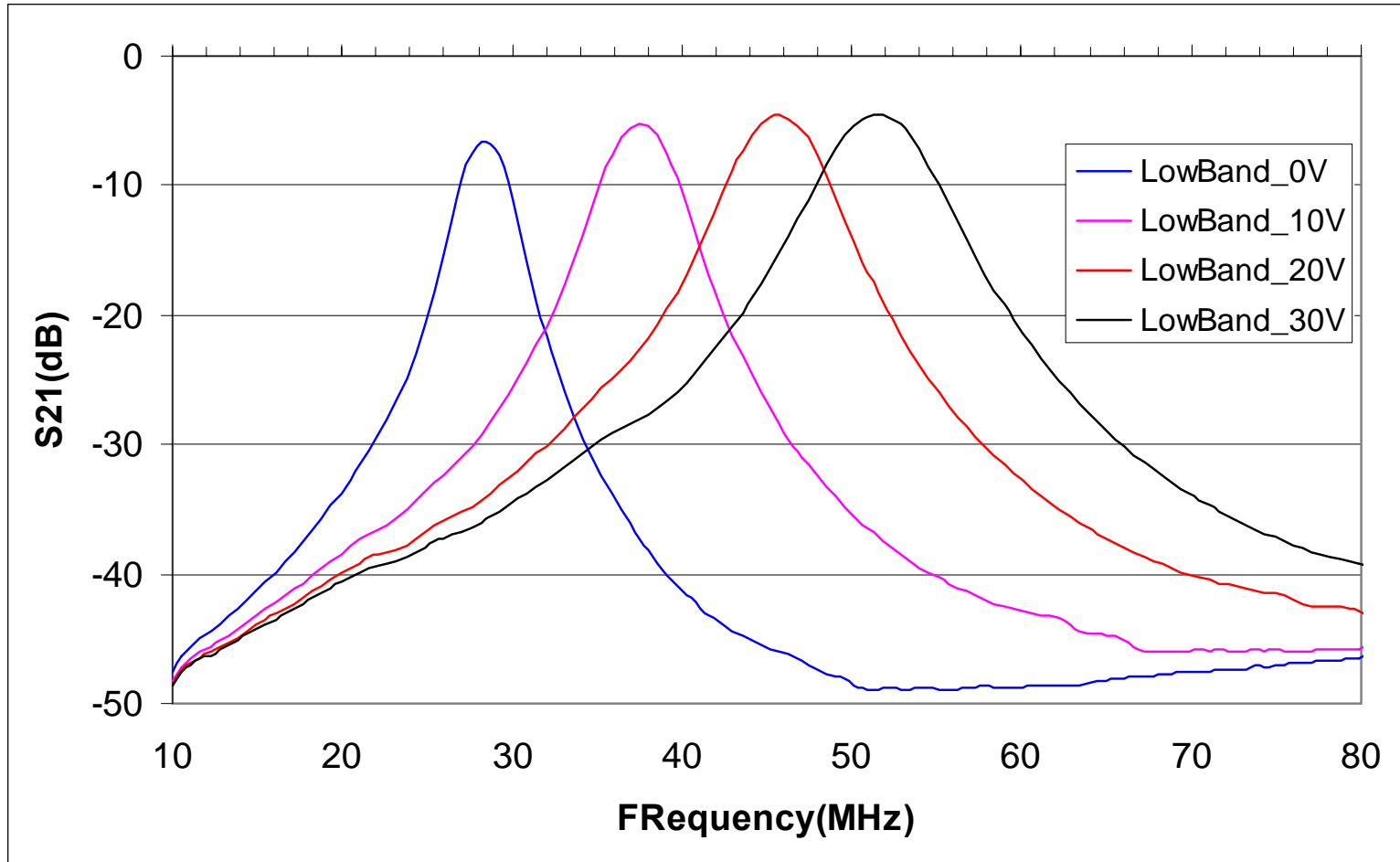
The DAC allows user to set 8 output channels. The control windows provide for setting the maximum and minimum values expected for the temperature and frequency.

# Full Band Filter Frequency Response

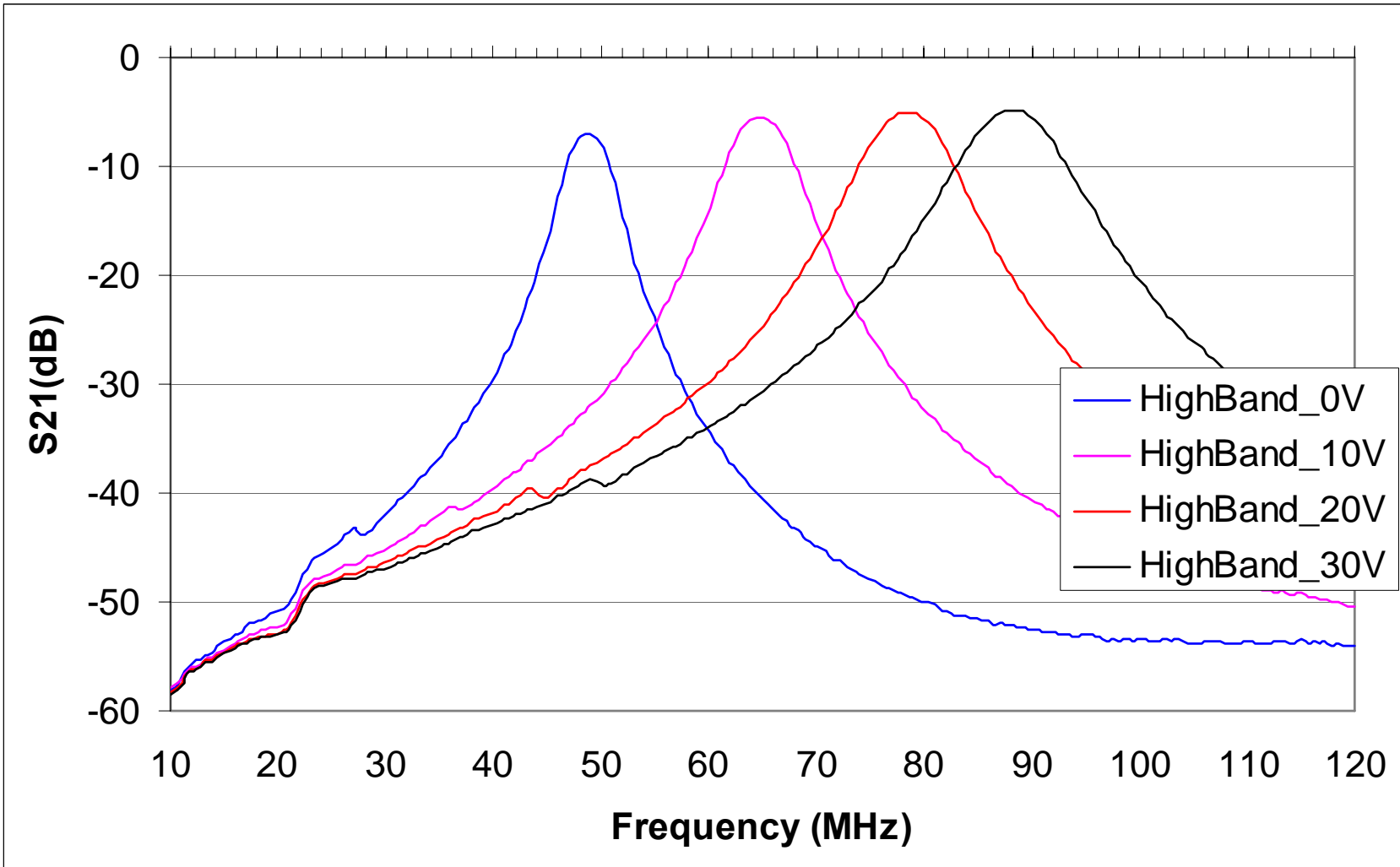


The measurement results show 4.5dB bandwidth of filter is  $< \pm 5\%$ , 30dB rejection is over  $\pm 27\%$ .

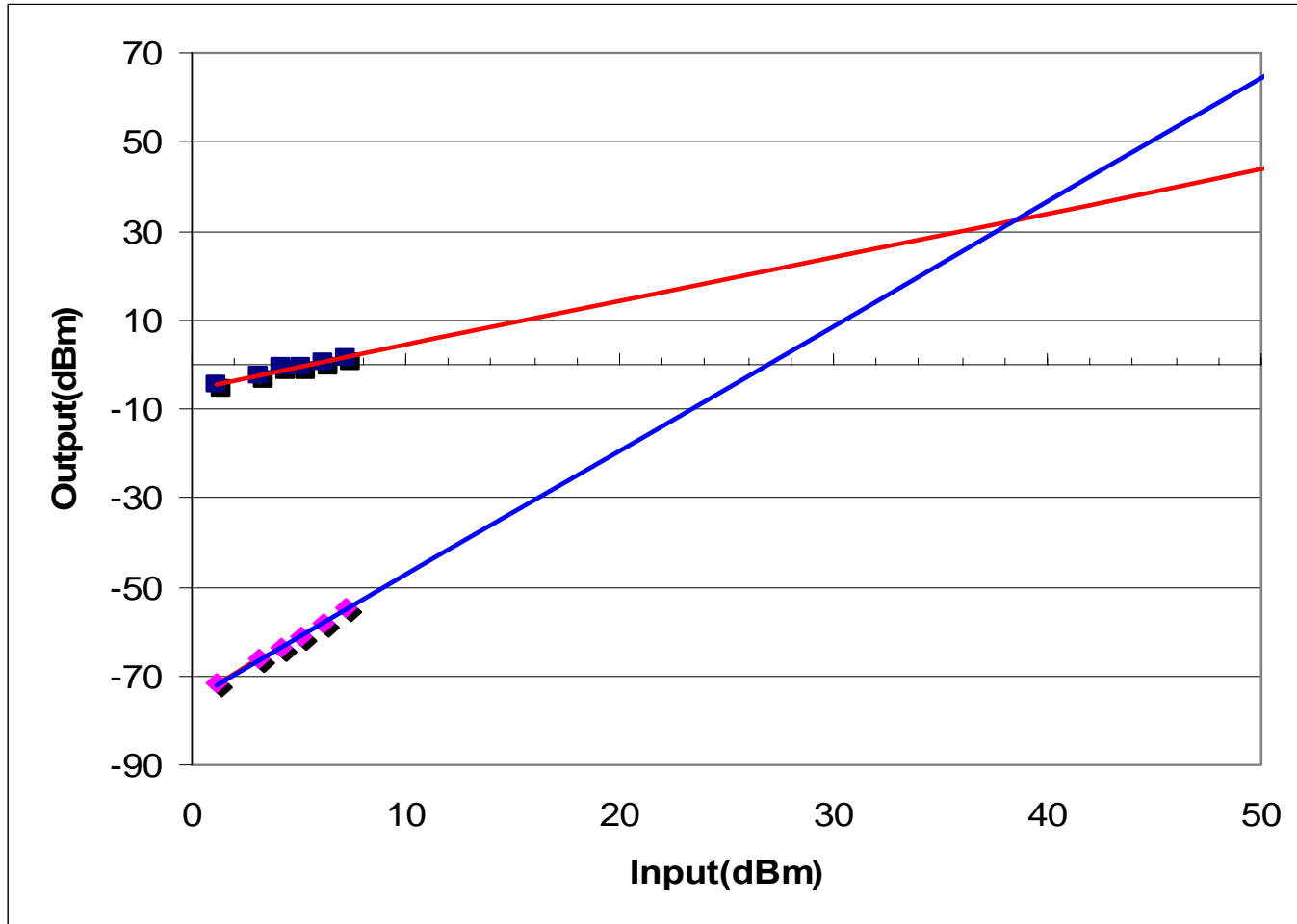
# Filter Low Band Frequency Response



# Filter High Band Frequency Response

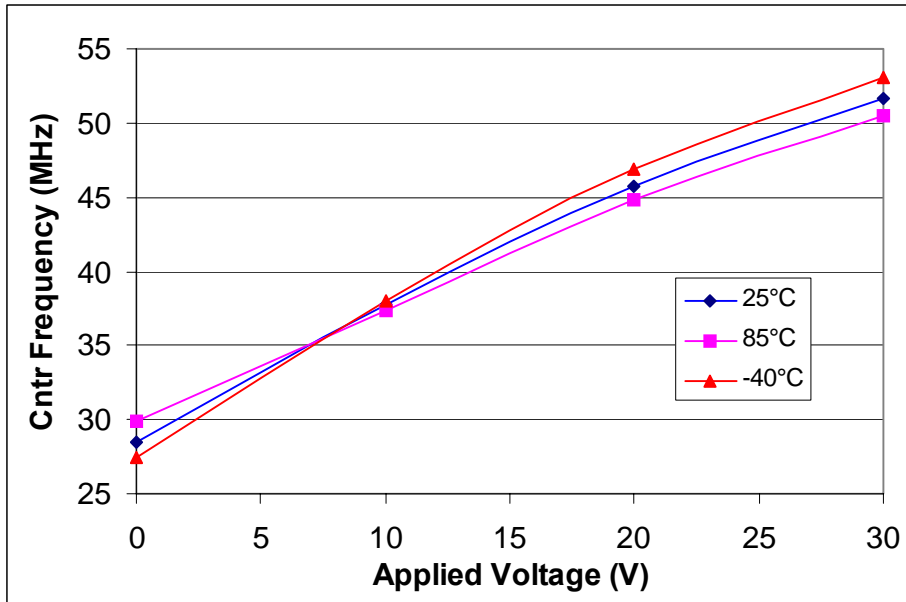


# Bandpass filter IIP3 Testing

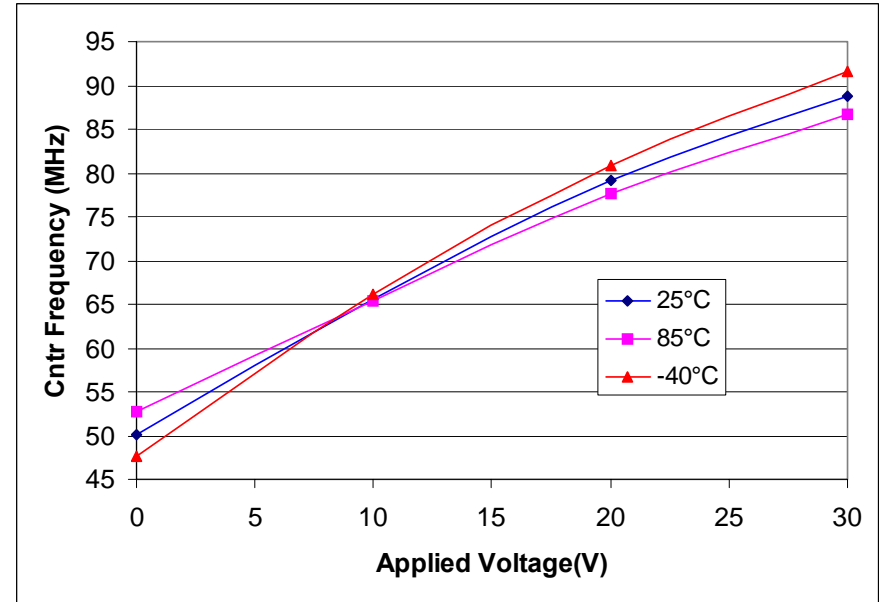


**Tunable filter IIP3 is over 40.5dBm at 30MHz,  $\Delta f$  is 25KHz.**

# Tunable Filter Temperature Response Test



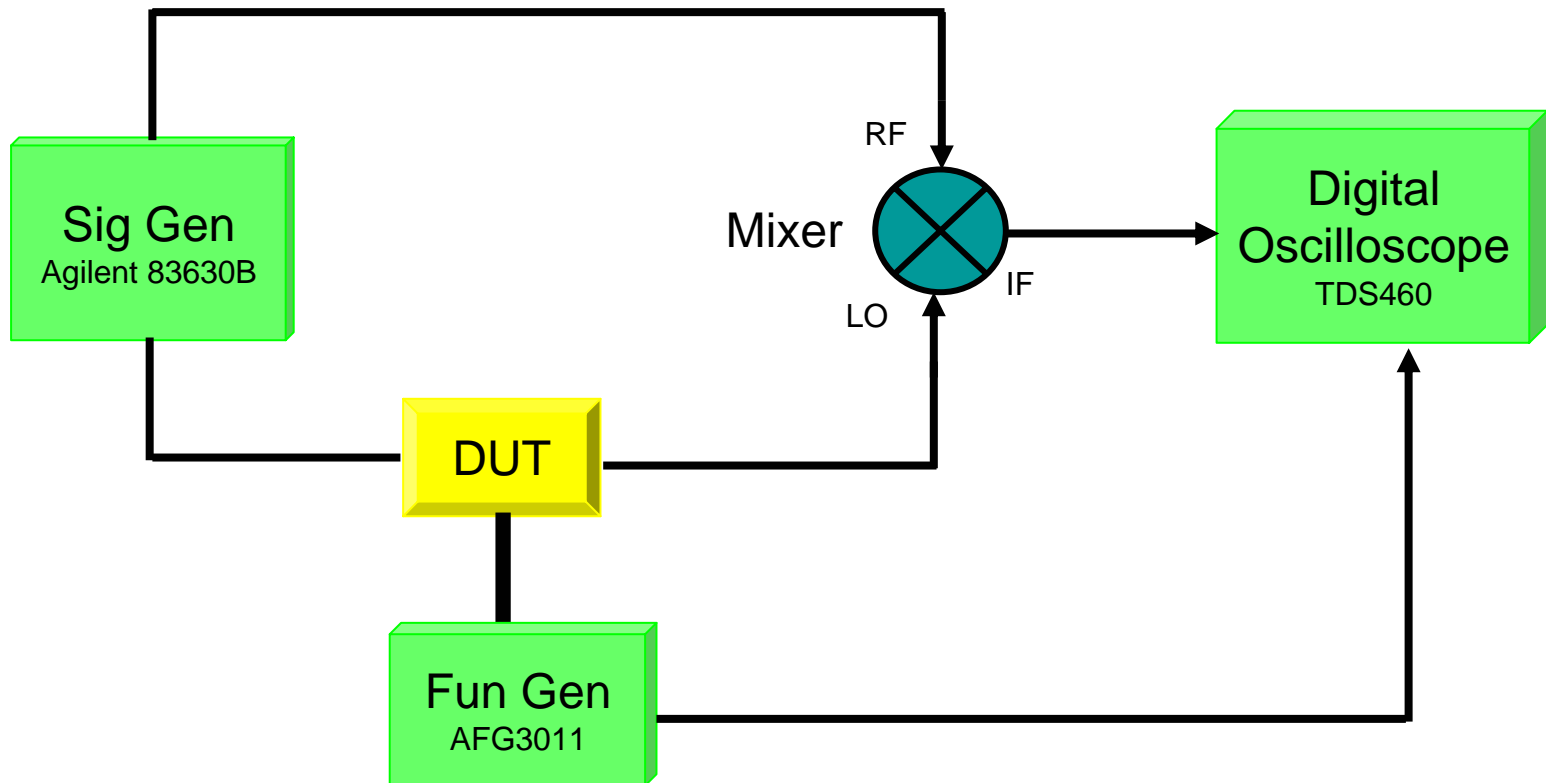
Low band



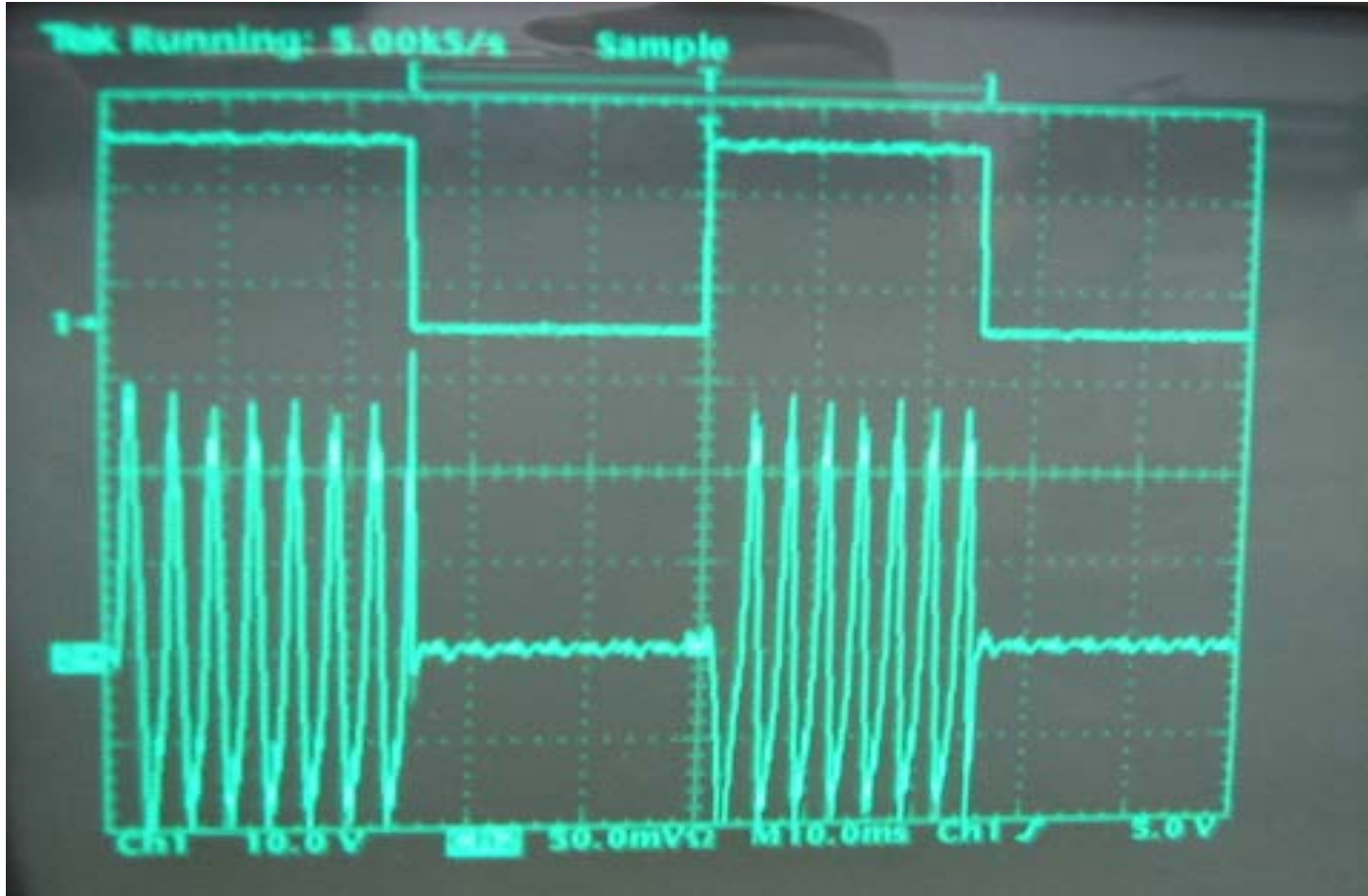
High Band

Filter Center Frequency vs. Applied voltage over Temperature

# Schematic of Testing Set-up

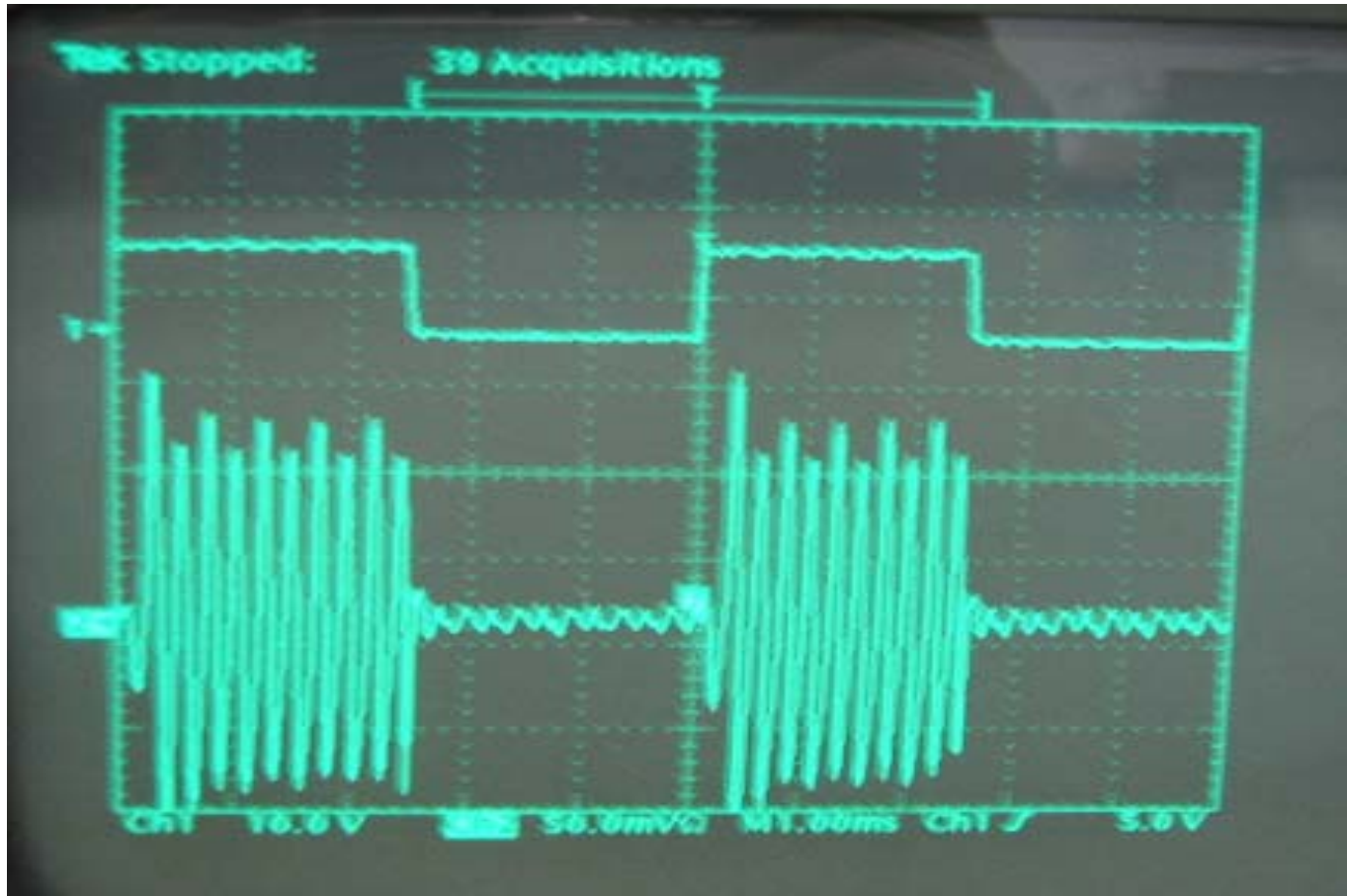


*High Band Transition Time: Bias resistor=20kohm, from 0V to 20V*



**Switch time >8ms**

*Low Band Transition Time: Bias resistor=1.5kohm, from 0V to 20V*



**Switch time >600us**