



中国科学技术大学

University of Science and Technology of China

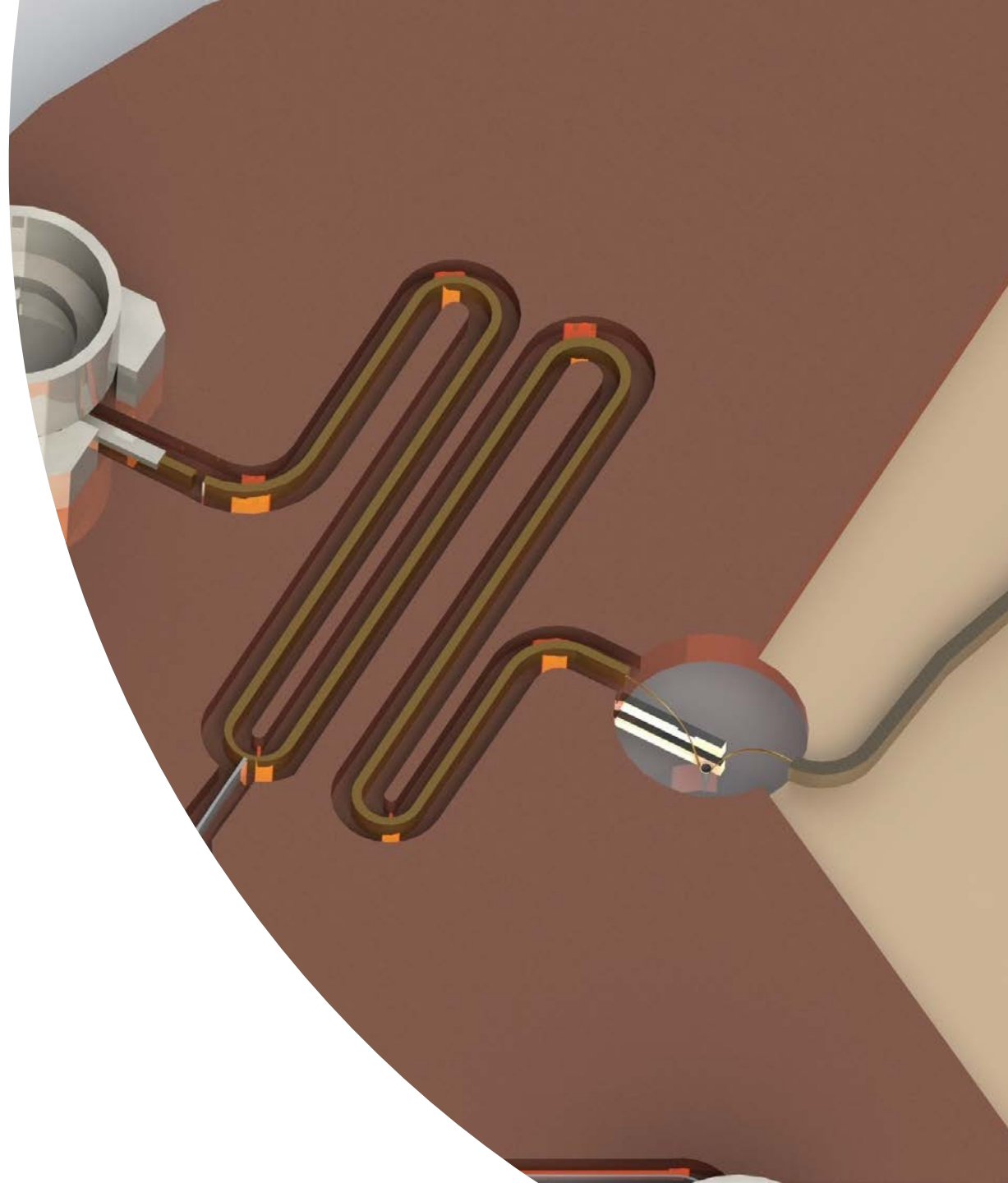
微波阻抗显微镜的搭建及改进

The Construction and Improvement of a Microwave Impedance Microscope

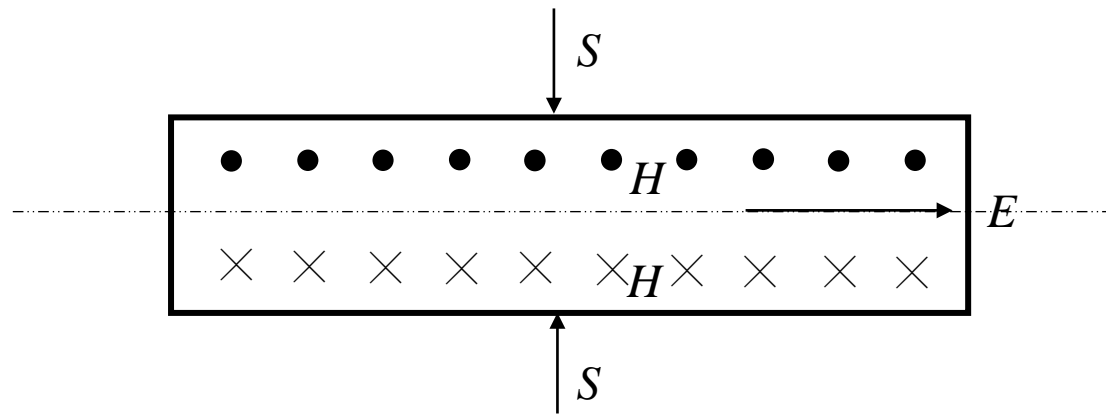
06/10/2020

裴宇翔

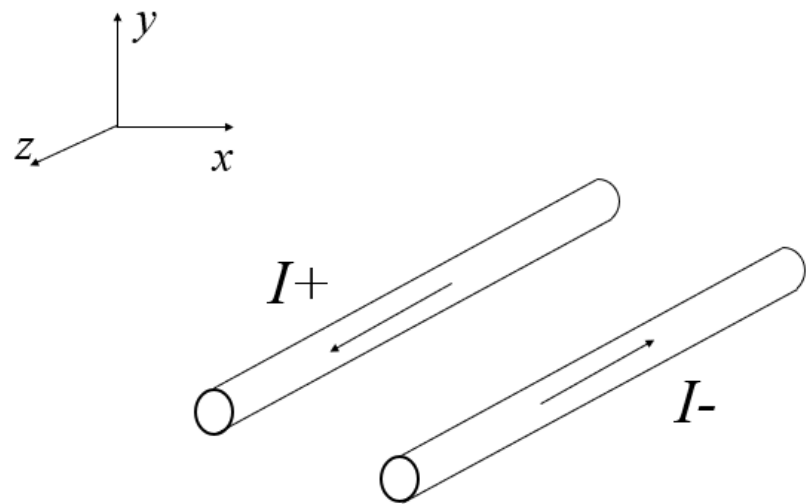
- 微波电路基础
- 微波探测原理
- 微波阻抗显微系统



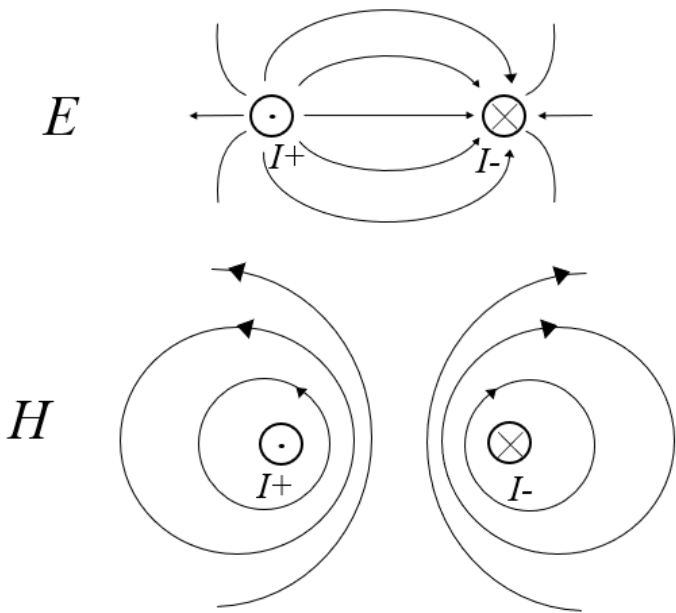
普通导线与传输线



普通导线的电磁场分布

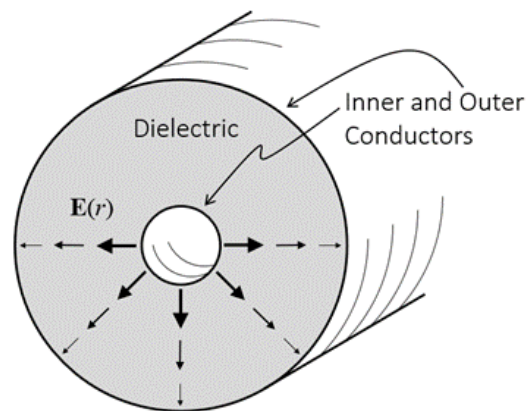


双导线模型

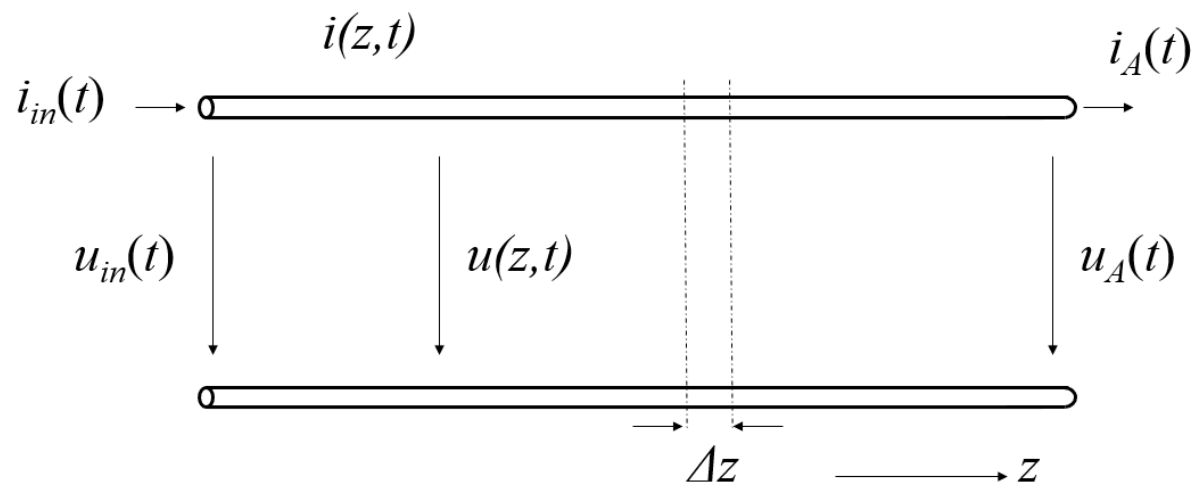


双导线横截面内的电场磁场分布

传输线上的电压和电流



同轴线的中心
导体和外部导体



前向波 后向波

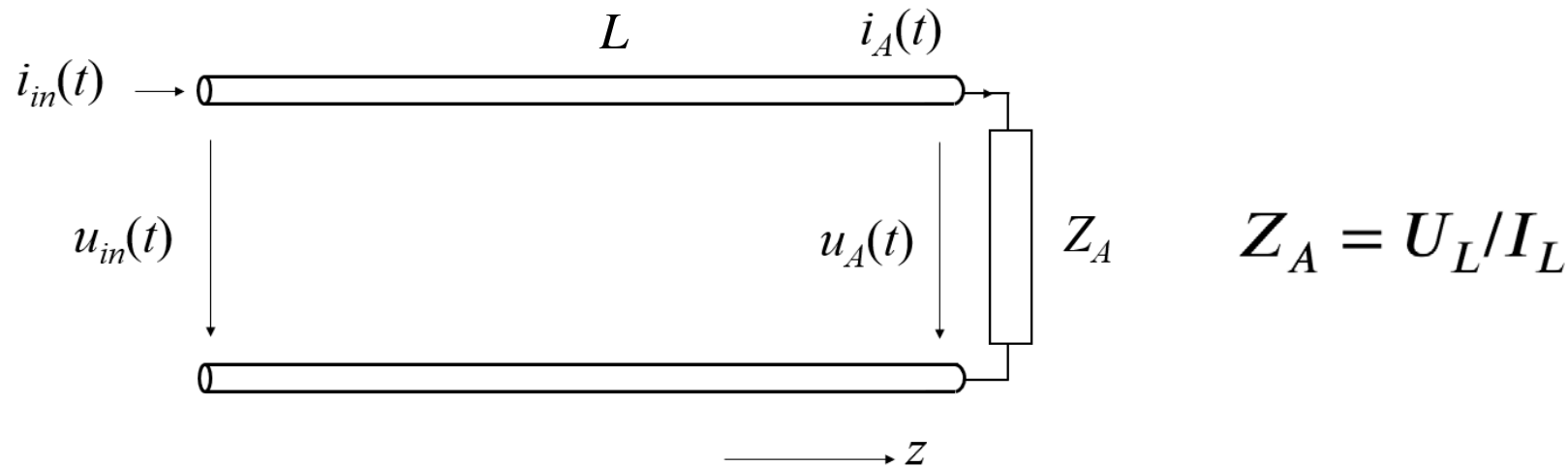
$$U(z) = U_f e^{-\gamma z} + U_r e^{\gamma z}$$

$$I(z)Z_0 = U_f e^{-\gamma z} - U_r e^{\gamma z}$$

特征阻抗



带负载的传输线



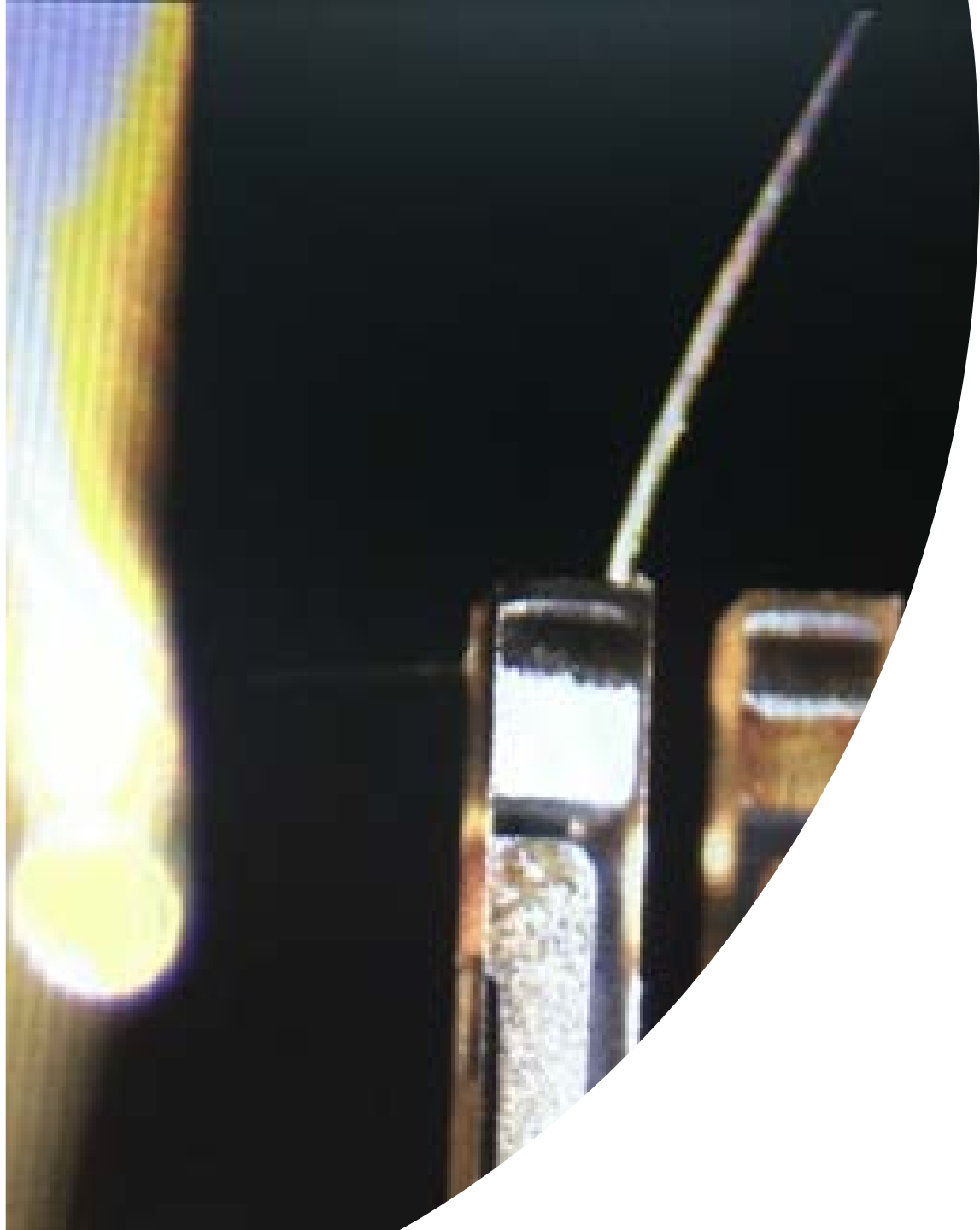
$$U_0 = U_f + U_r$$

$$I_0 Z_0 = U_f - U_r$$

$$U_L = U_f e^{-i\beta L} + U_r e^{i\beta L}$$

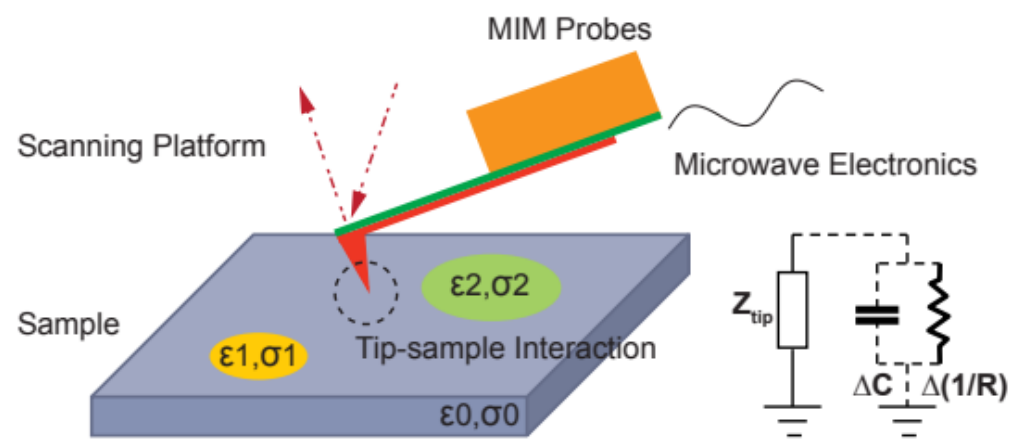
$$I_L Z_0 = U_f e^{-i\beta L} - U_r e^{i\beta L}$$

反射系数 $\Gamma(L) = \frac{U_r e^{i\beta L}}{U_f e^{-i\beta L}} = \Gamma(0) e^{-2i\beta L} = \frac{Z_A - Z_0}{Z_A + Z_0}$



- 微波电路基础
- 微波探测原理
- 微波阻抗显微系统

共振匹配单元



MIM 测头部分示意图

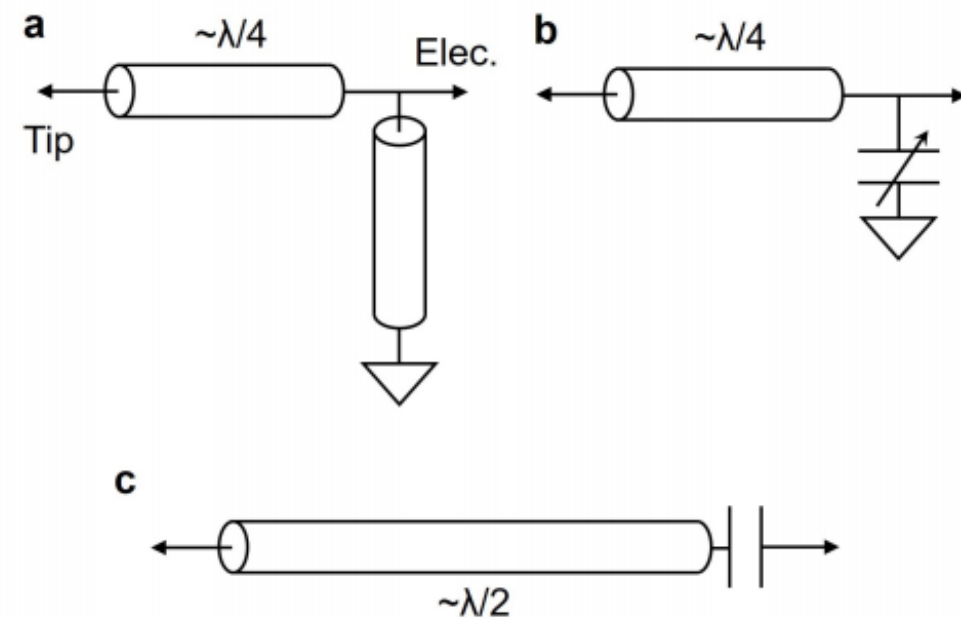
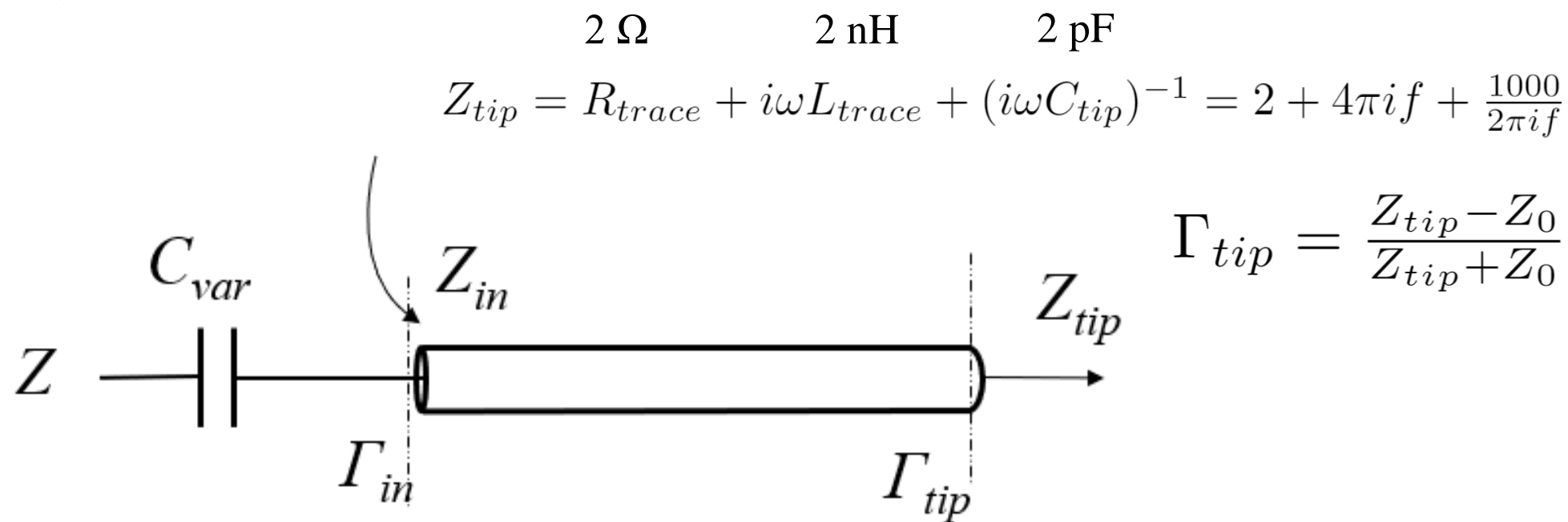


Figure 1.8. (a,b) Single-stub and lumped-element impedance matching networks for shielded cantilever probes. (c) Half-wavelength resonator matching network for TF-based sensors.



共振匹配单元的传输线模型

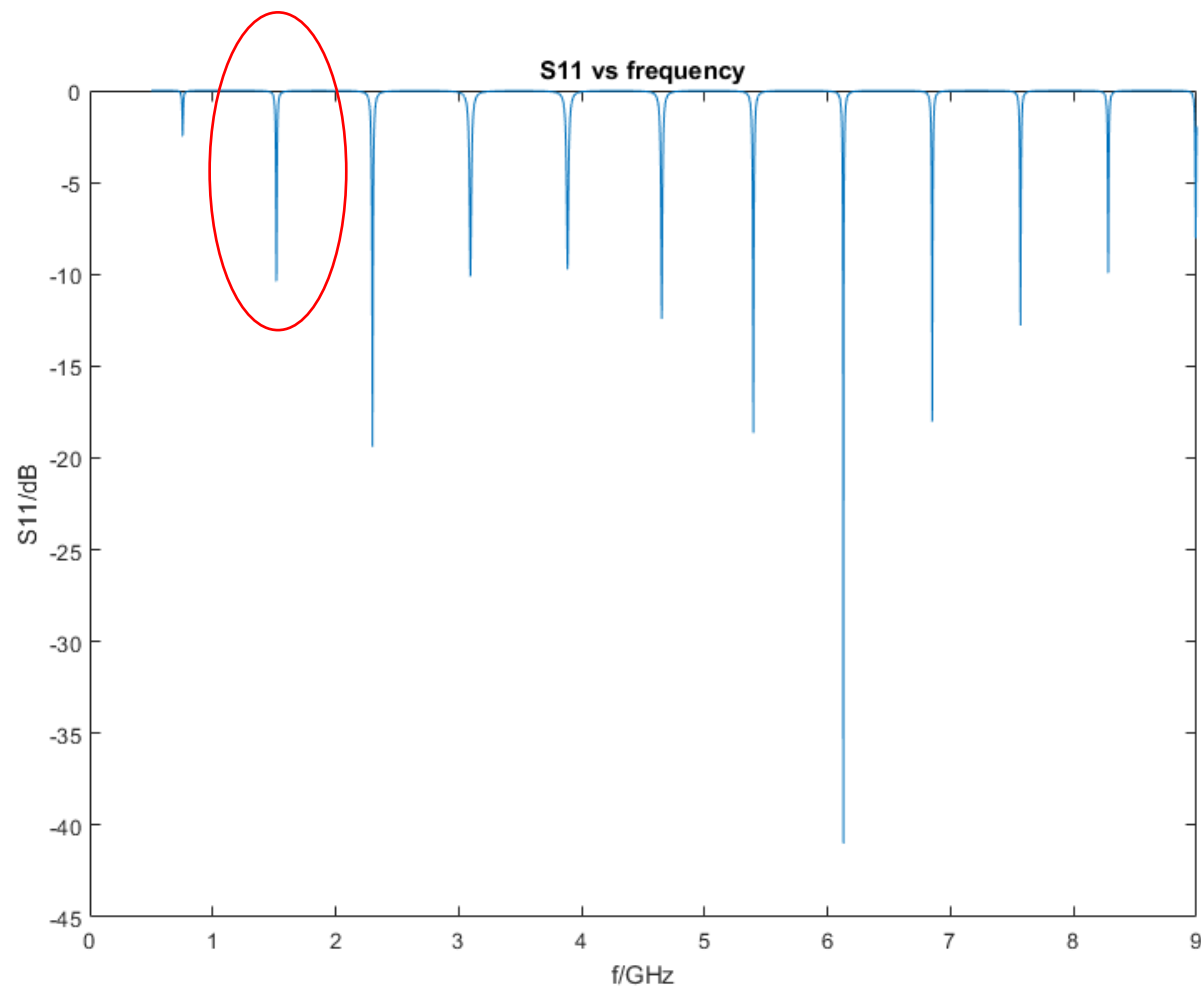


$$\Gamma_{in} = \Gamma_{tip} e^{-2i\beta L}$$

$$Z = Z_{in} + (i\omega C_{var})^{-1} = \frac{1 + \Gamma_{in}}{1 - \Gamma_{in}} + \frac{1000}{2\pi if C_{var}}$$

$$S_{11} = \frac{Z - Z_0}{Z + Z_0}$$

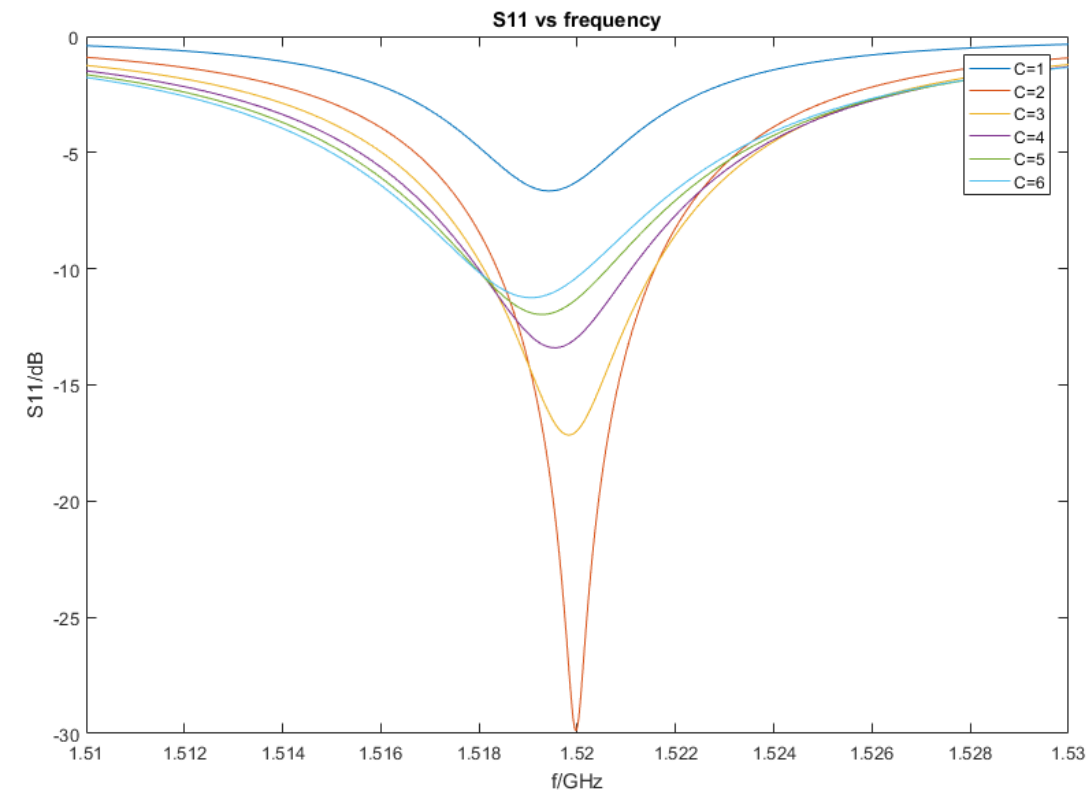
全频段共振峰分布



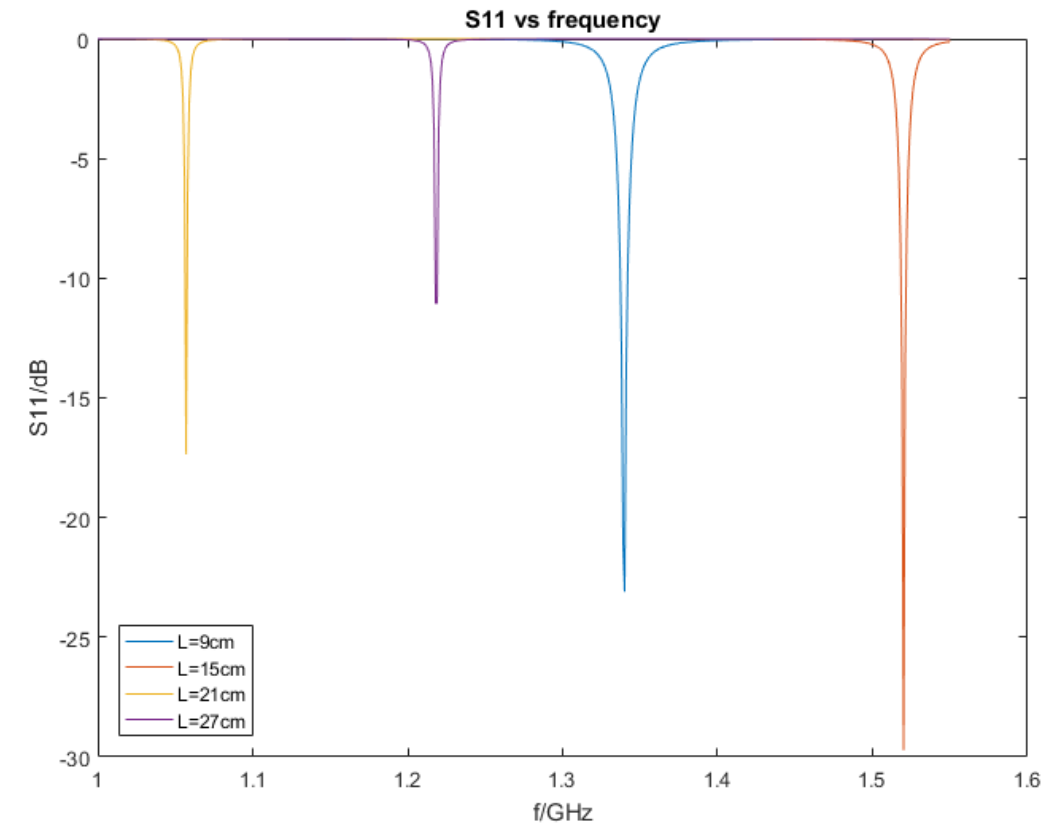
S_{11} 关于频率 f 的图像($C=9$ pF, $L=15$ cm)



共振峰随参数变化



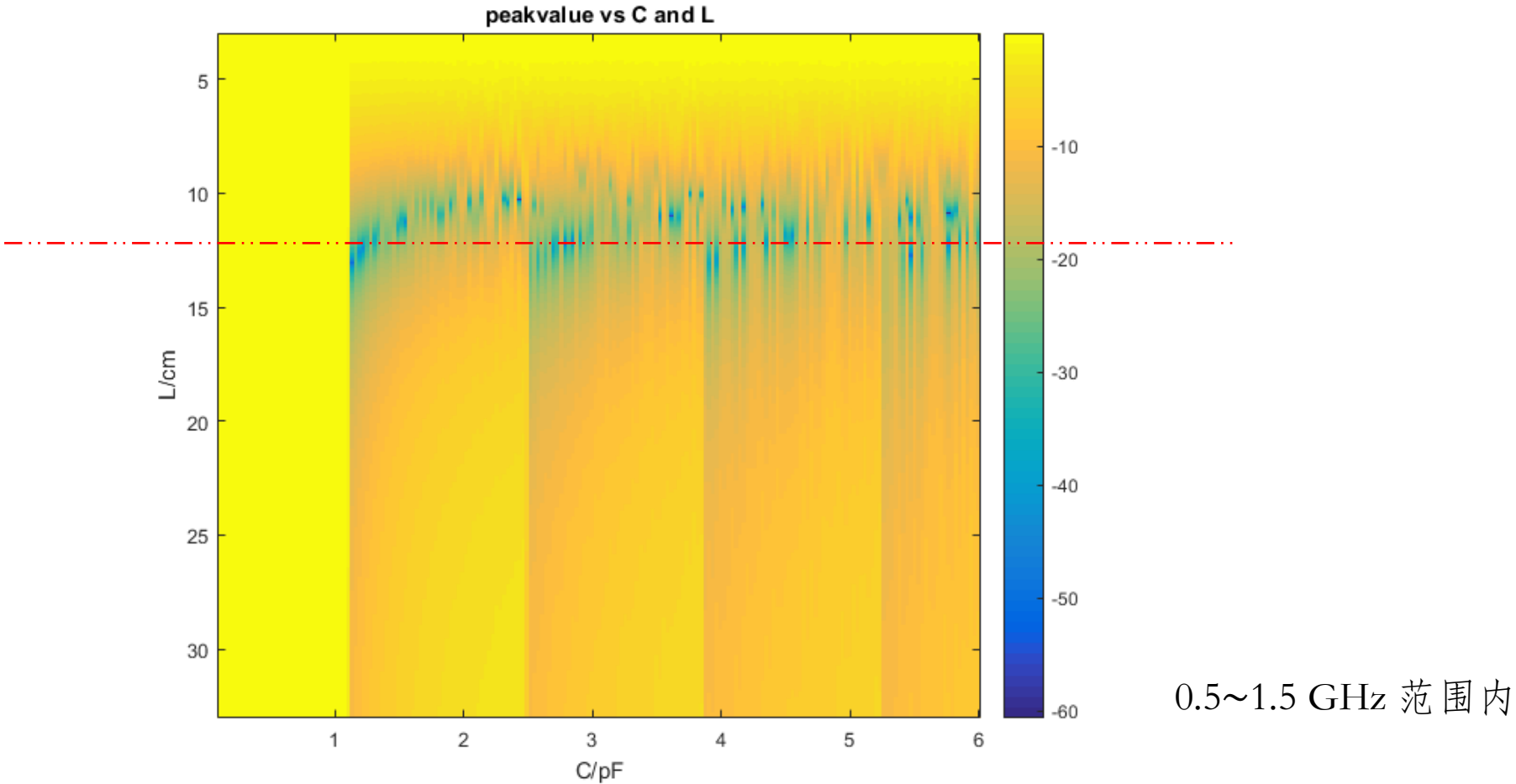
变化电容C



变化长度L



共振峰值关于C & L二维热图



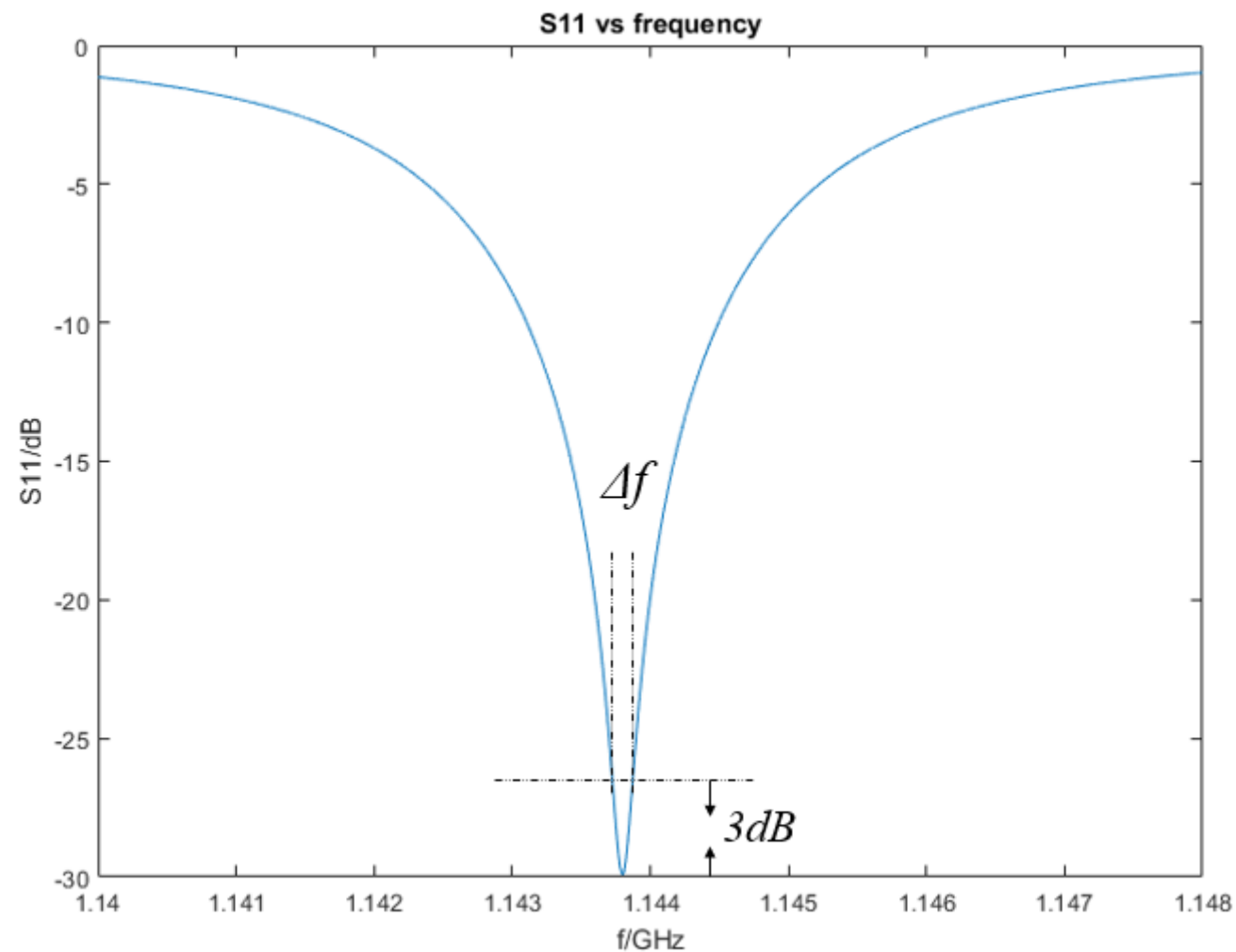
峰值关于可调电容 C 与传输线长度 L 的二维热图

共振峰对样品的响应

$$L = 19.5 \text{ cm}$$

$$C_{Var} = 1.8 \text{ pF}$$

$$Q = \frac{1143.8 \text{ MHz}}{0.132 \text{ MHz}} = 8665$$



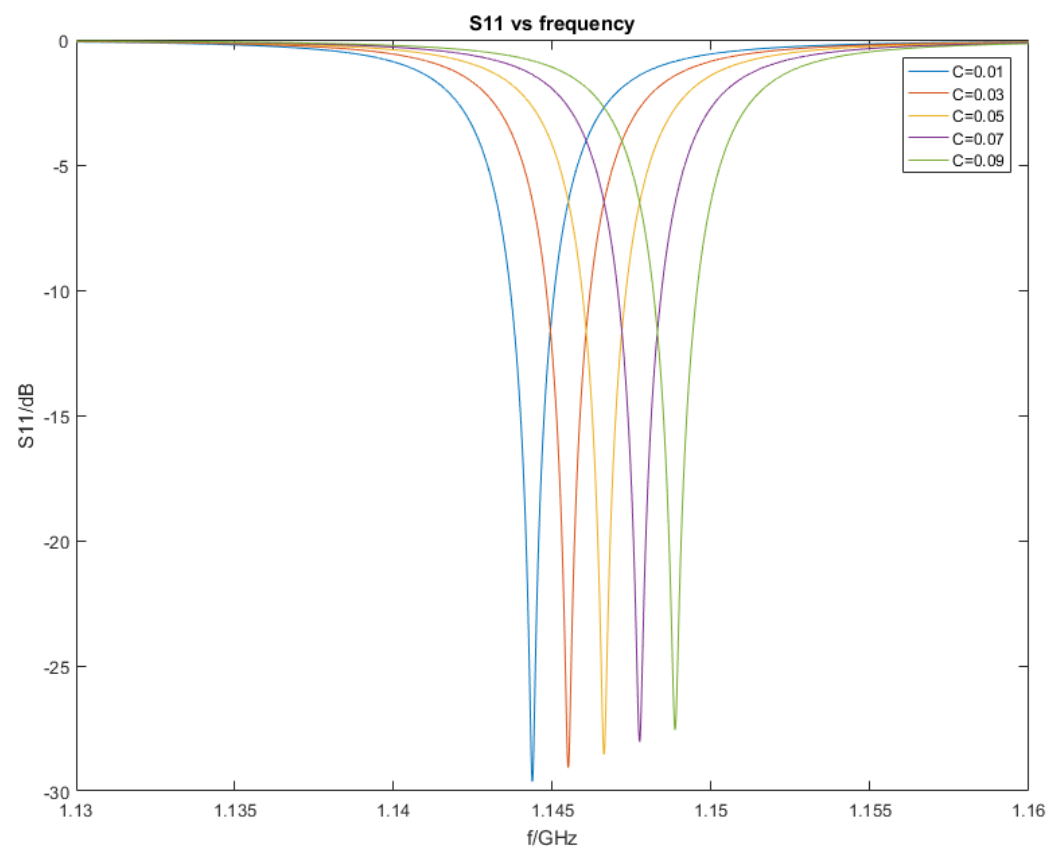
系统在 1.14 GHz 附近的共振峰



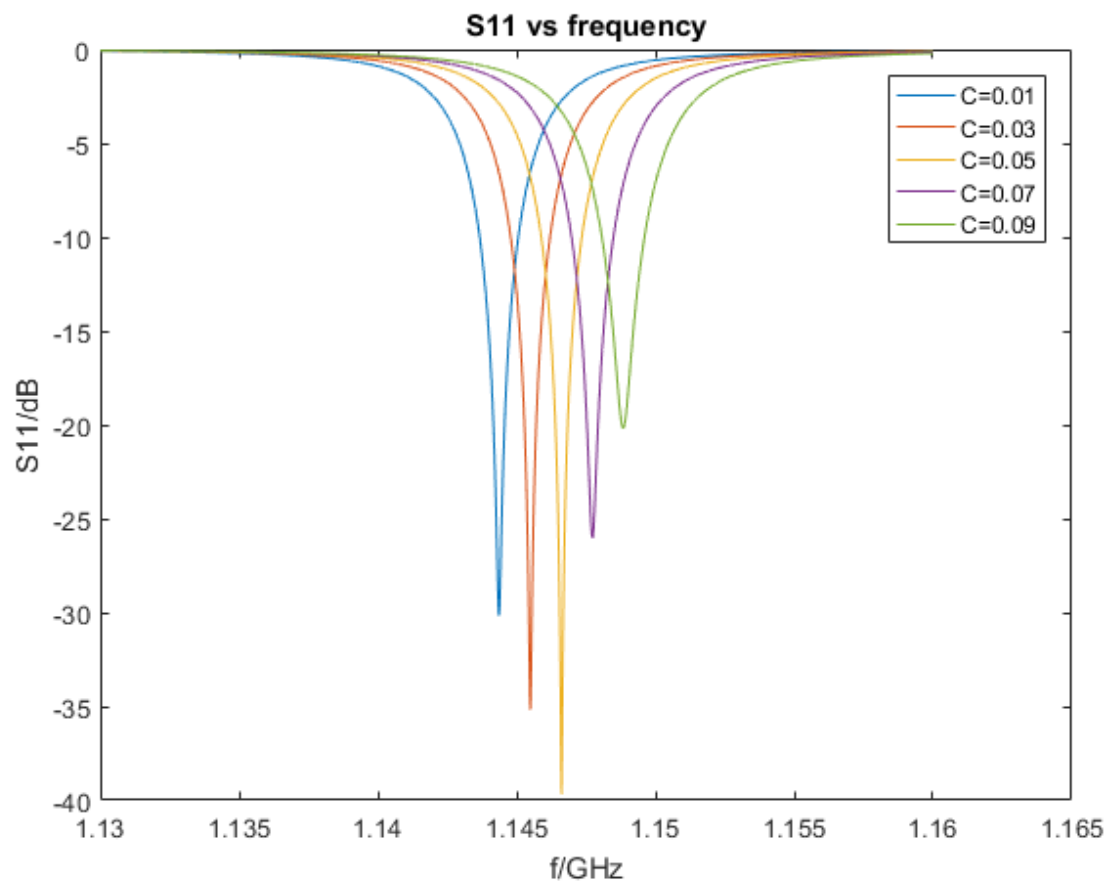
共振峰对样品电容的响应

$$Z_{sample} = R_{sample} + C_{sample} + L_{sample}$$

$$Z_{total} = \left(\frac{1}{Z_{tip}} + \frac{1}{Z_{sample}} \right)^{-1} = \left(\frac{1}{Z_{tip}} + \frac{1}{R_s + i\omega L_s + (i\omega C_s)^{-1}} \right)^{-1}$$



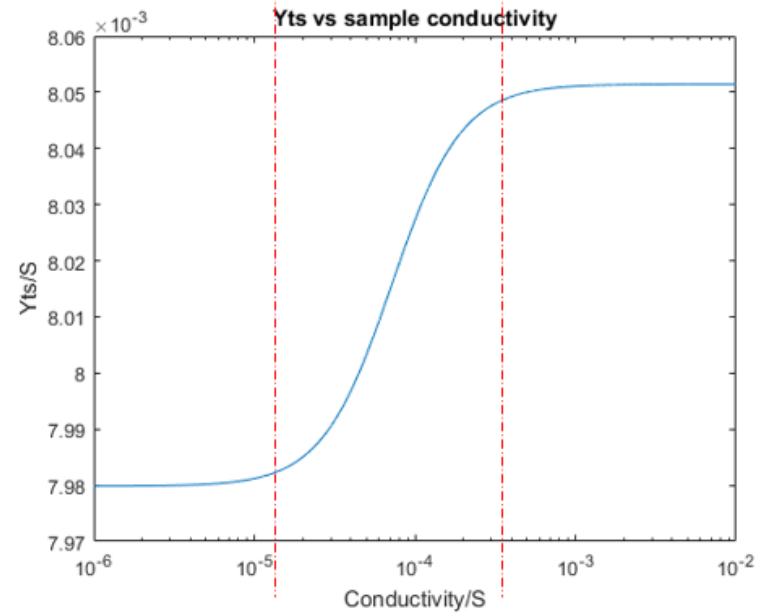
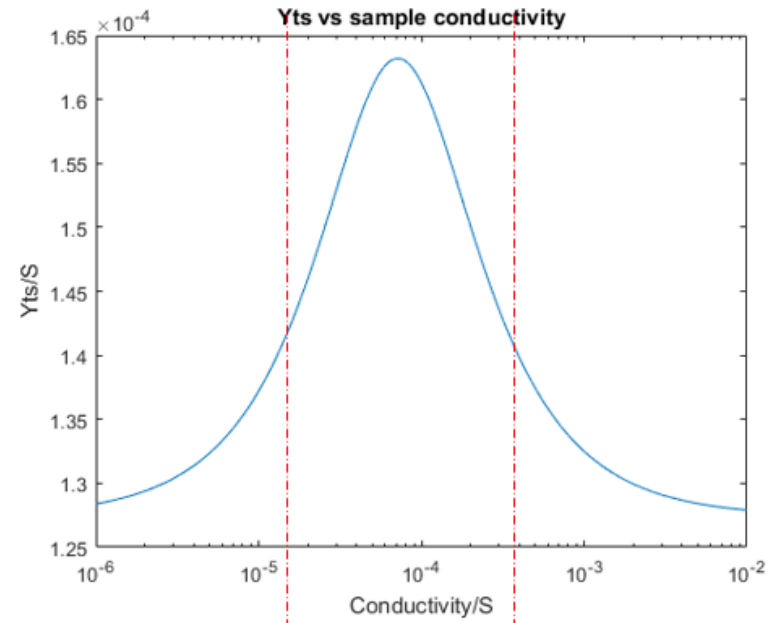
变化Cs (Rs=0)



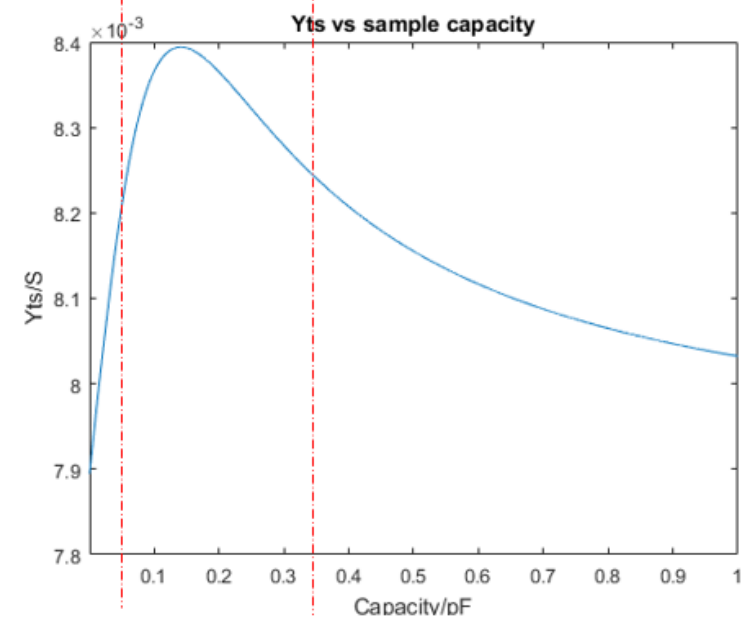
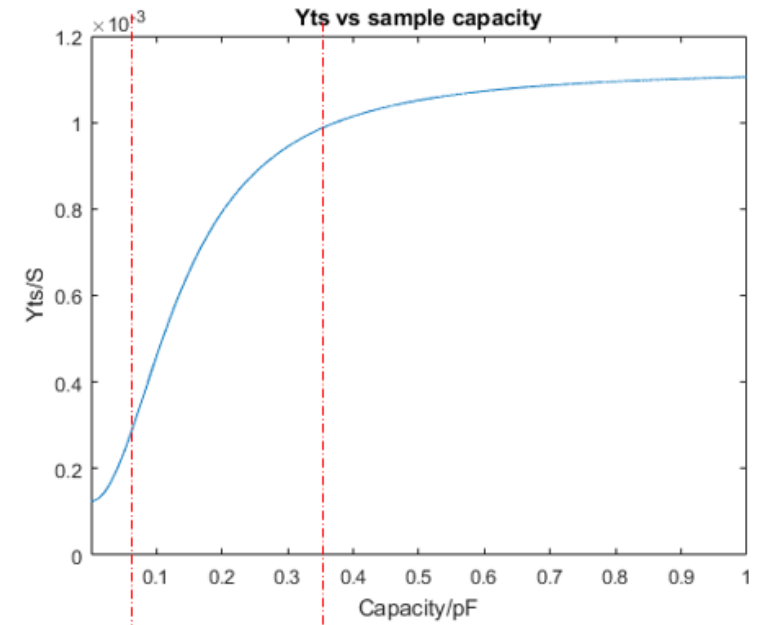
变化Cs (Rs=100 Ω)



电阻灵敏窗口

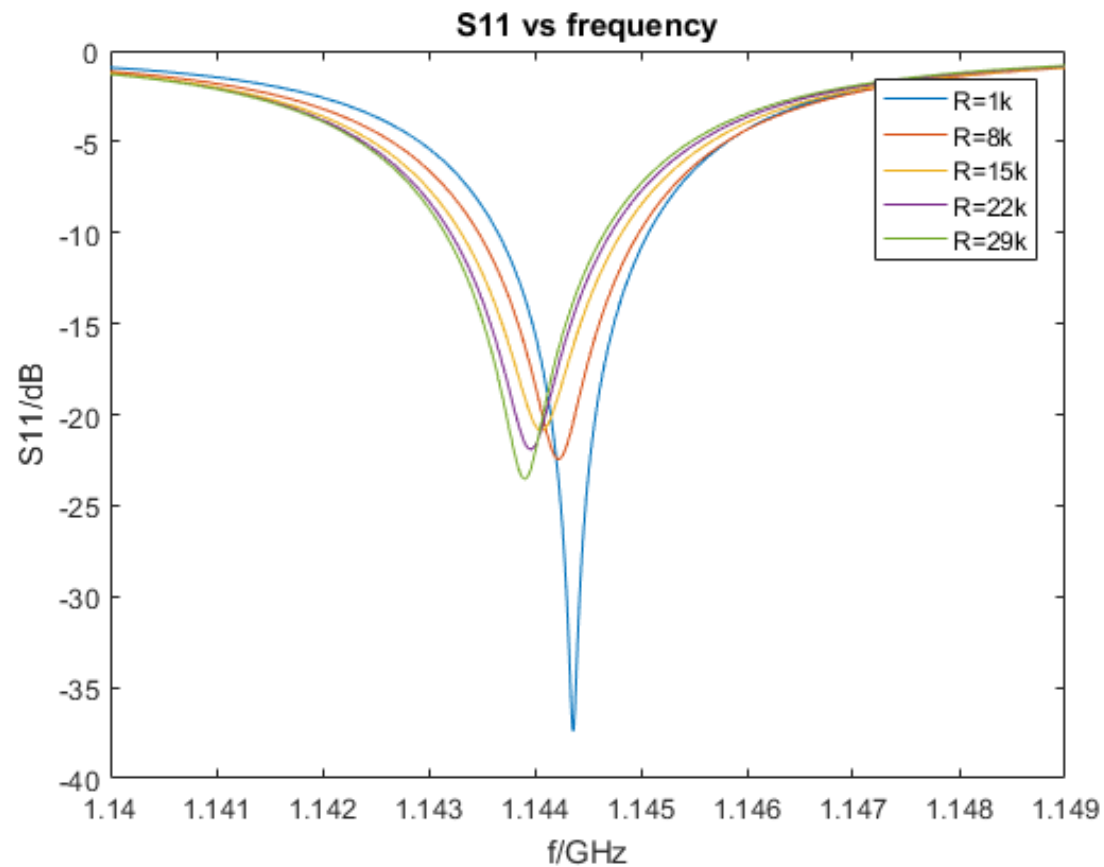


电容灵敏窗口

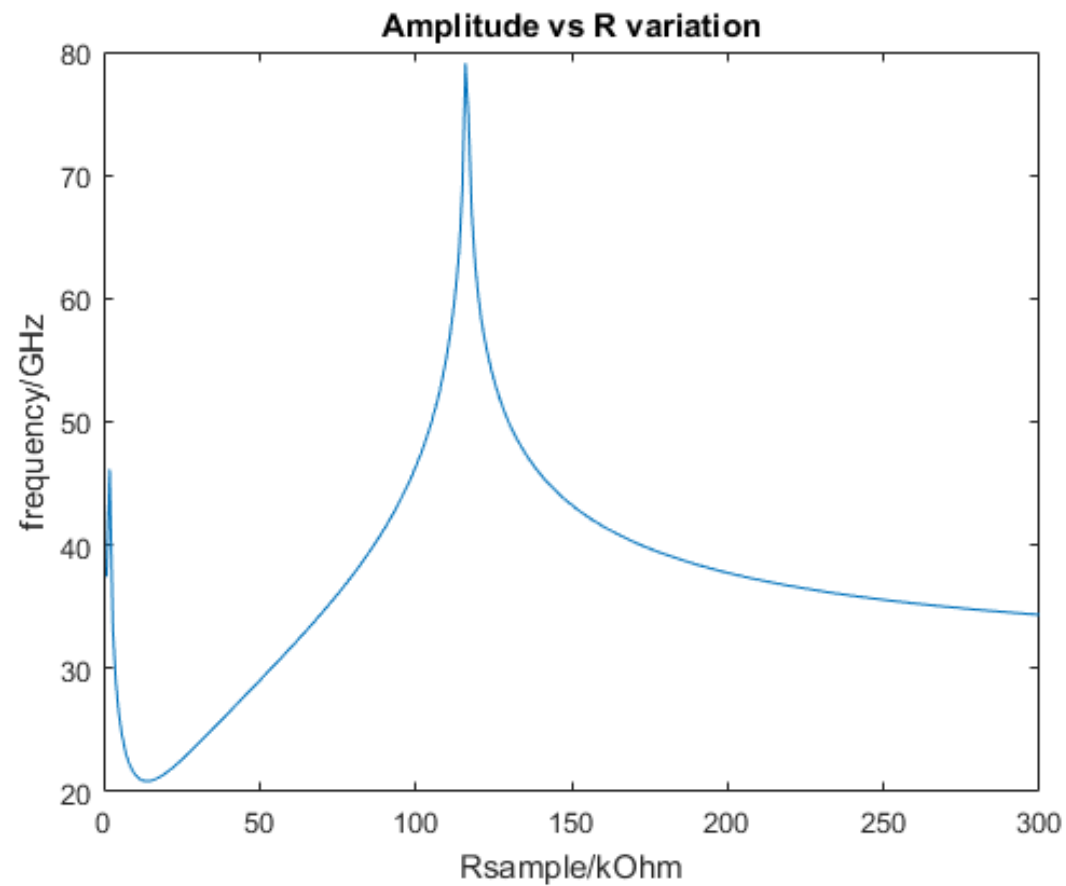




共振峰对样品电阻的响应



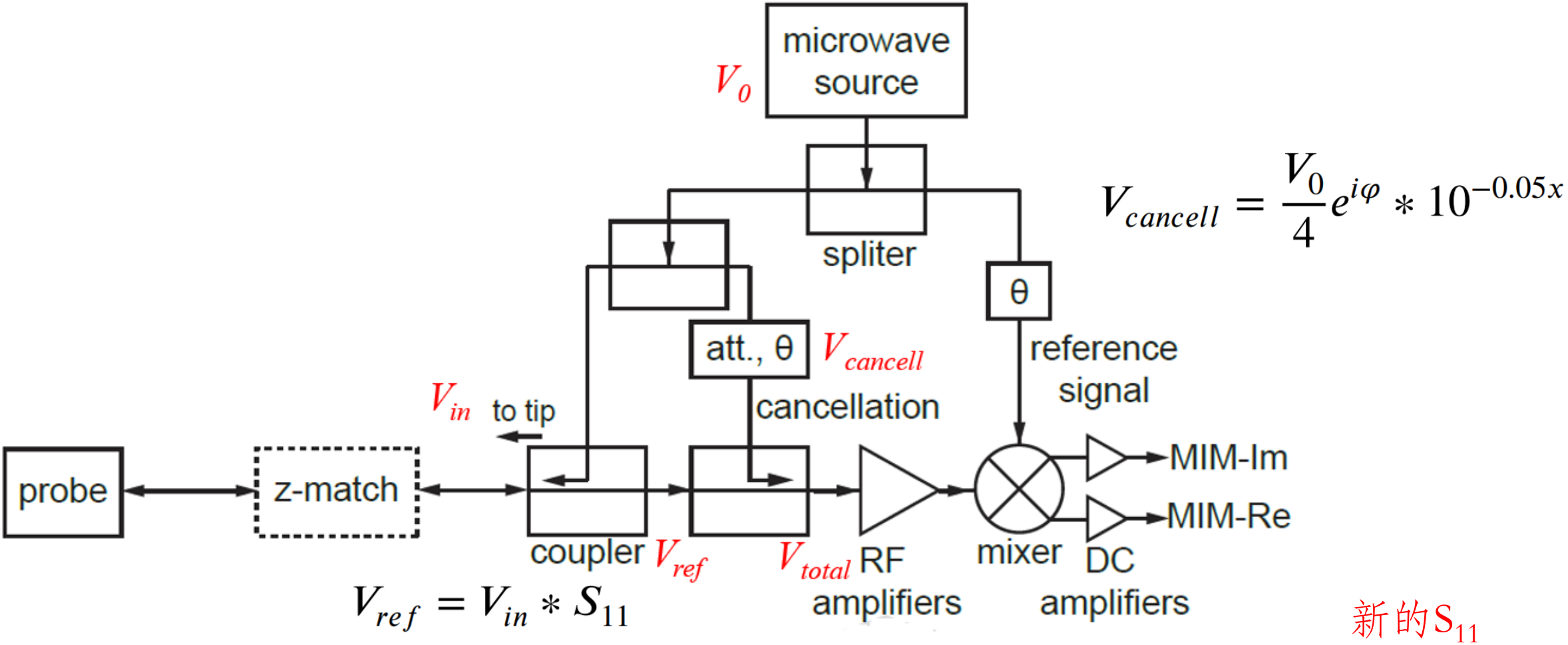
变化 R_s



峰值关于 R_s 的变化关系

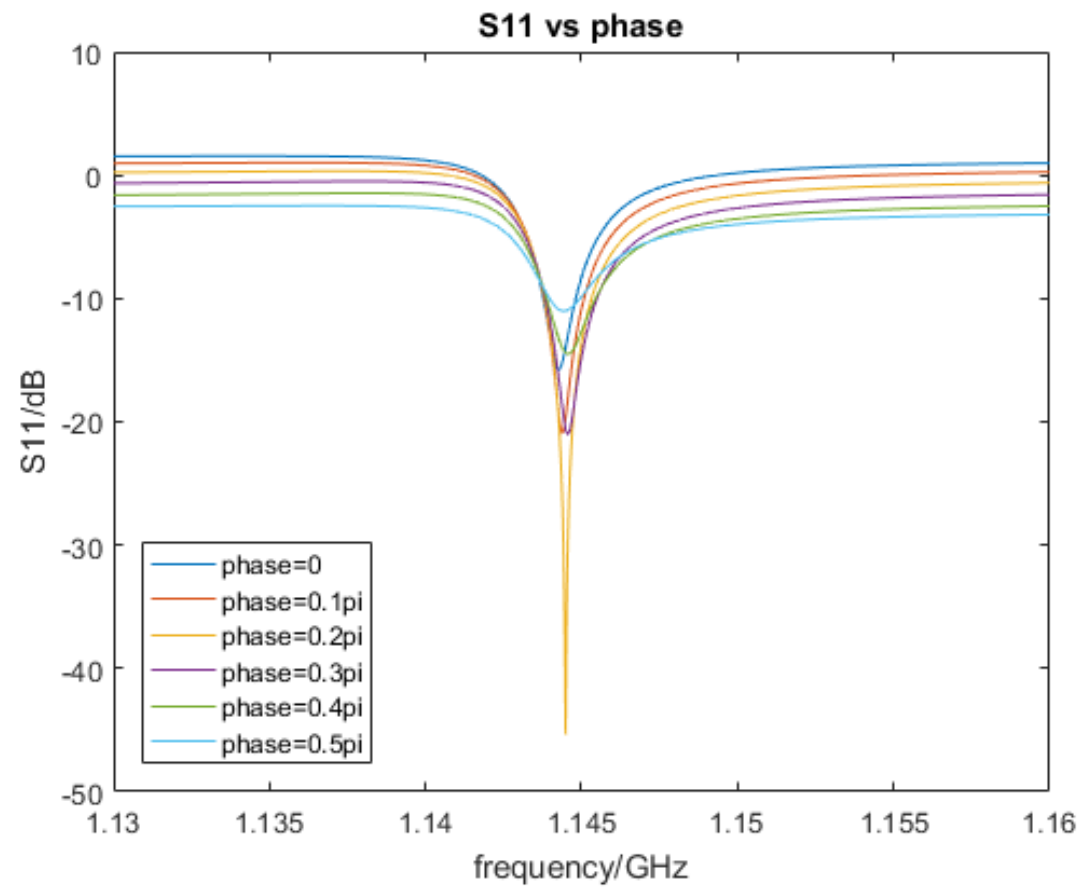
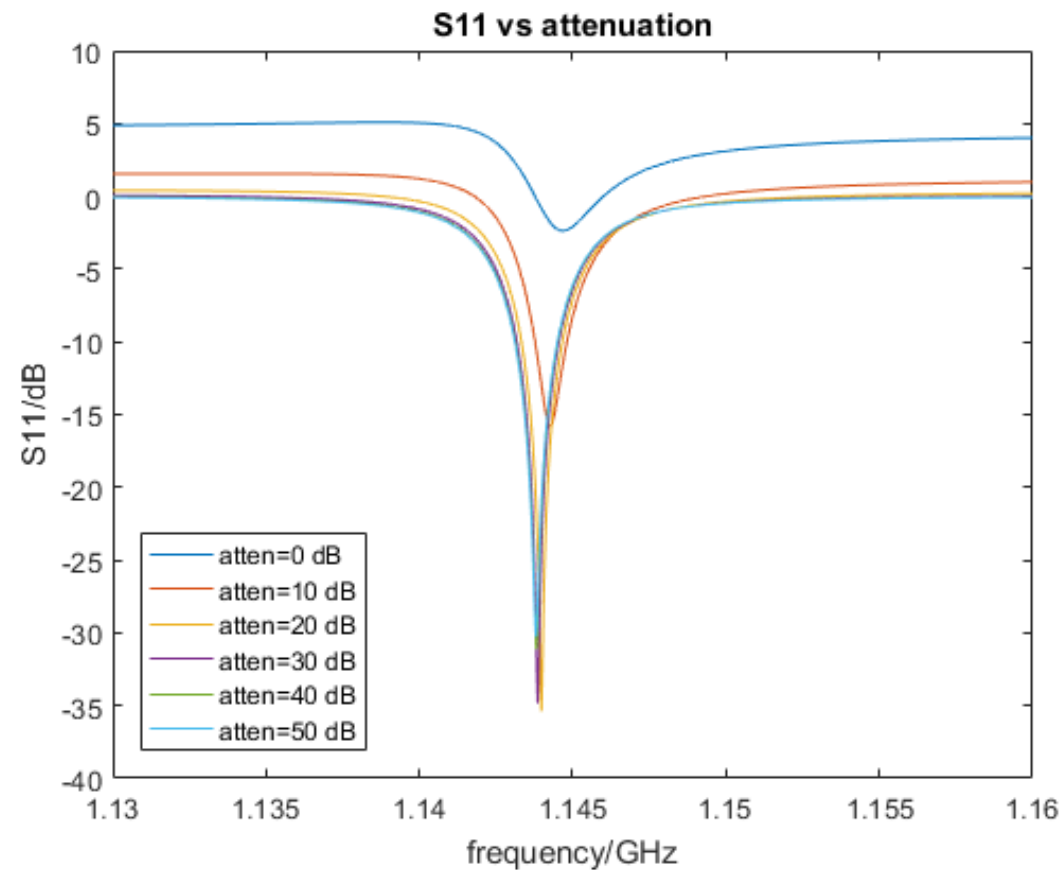


抵消(Cancellation)的实现



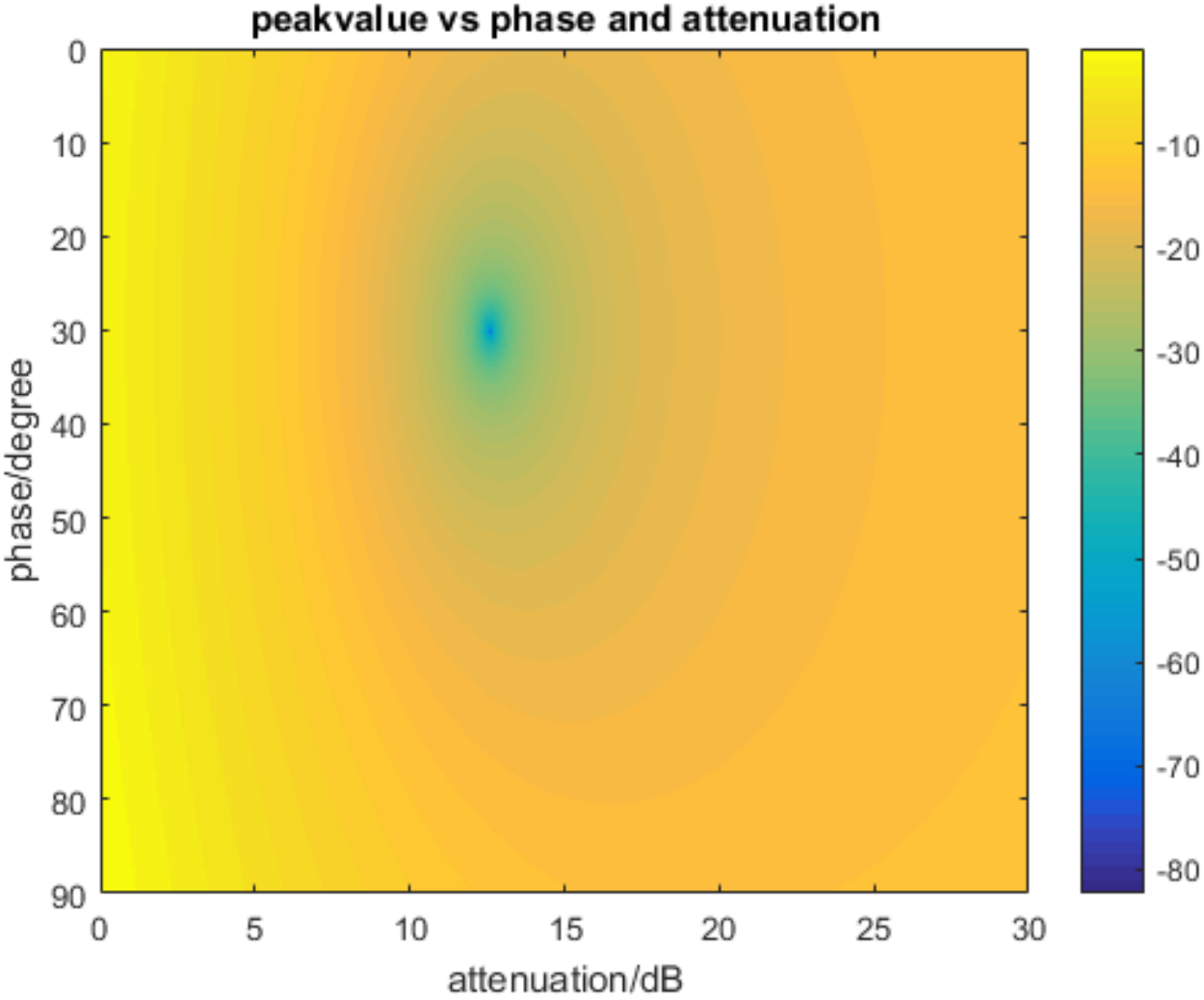
$$V_{total} = k * V_{cancell} + V_{ref} = \frac{kV_0}{4} (S_{11} + e^{i\varphi} * 10^{-0.05x})$$

抵消后共振峰与 α 和 φ 的依赖关系



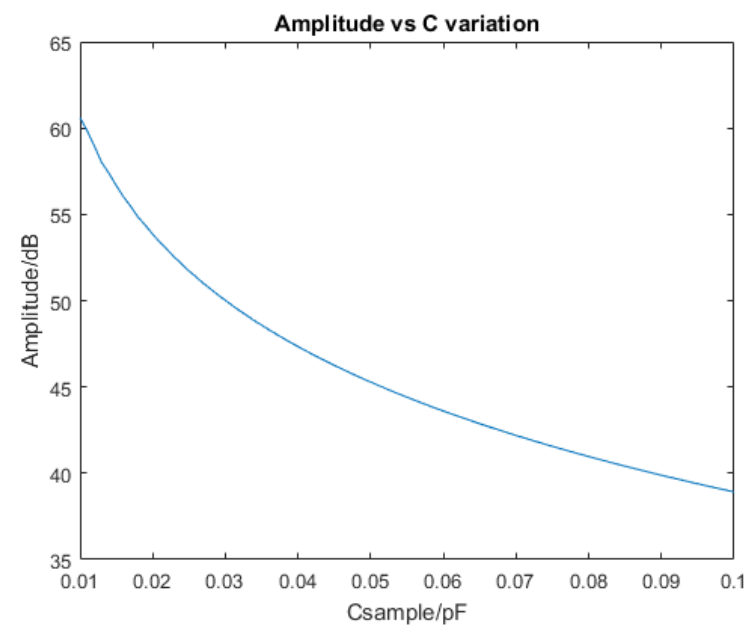
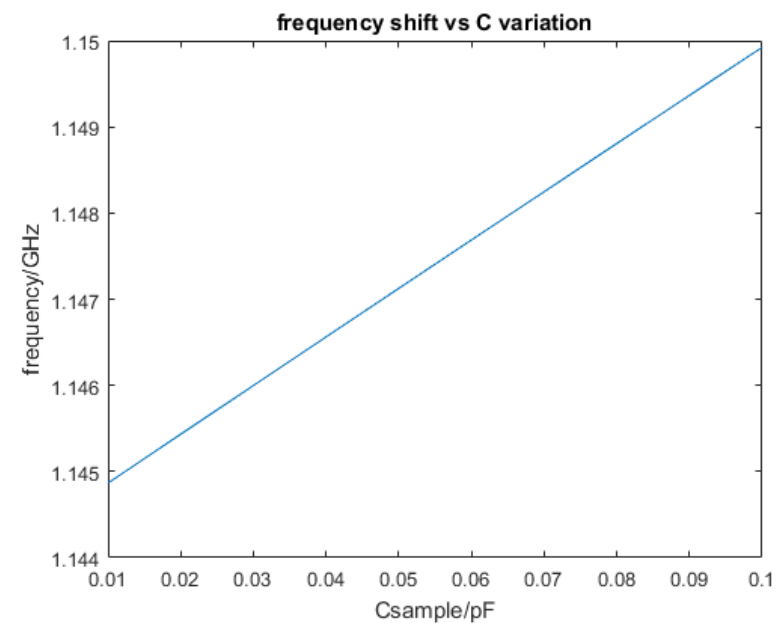
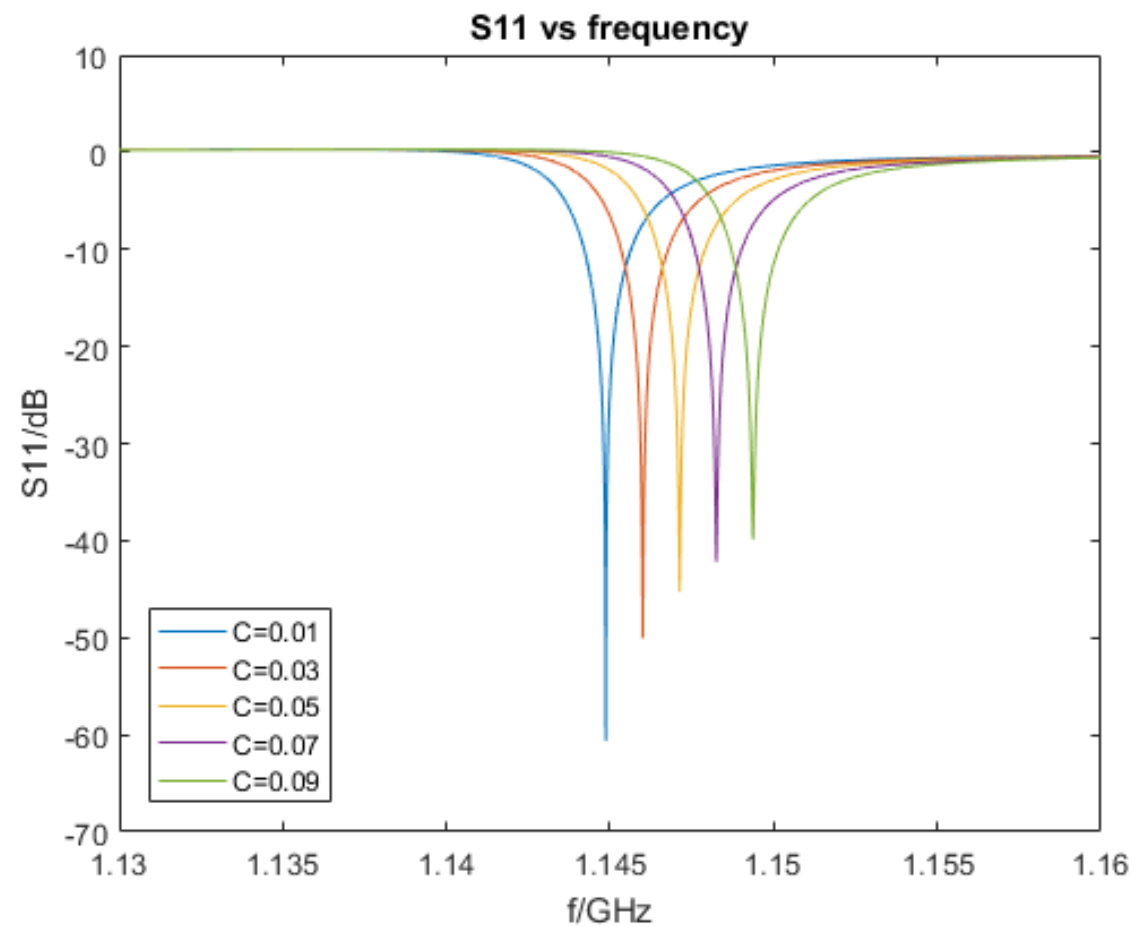


抵消后共振峰与 α 和 φ 的二维热图

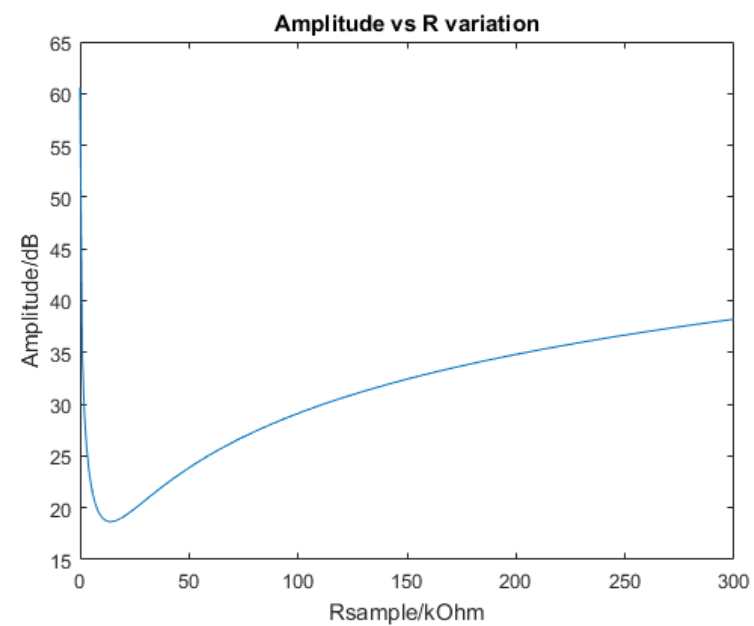
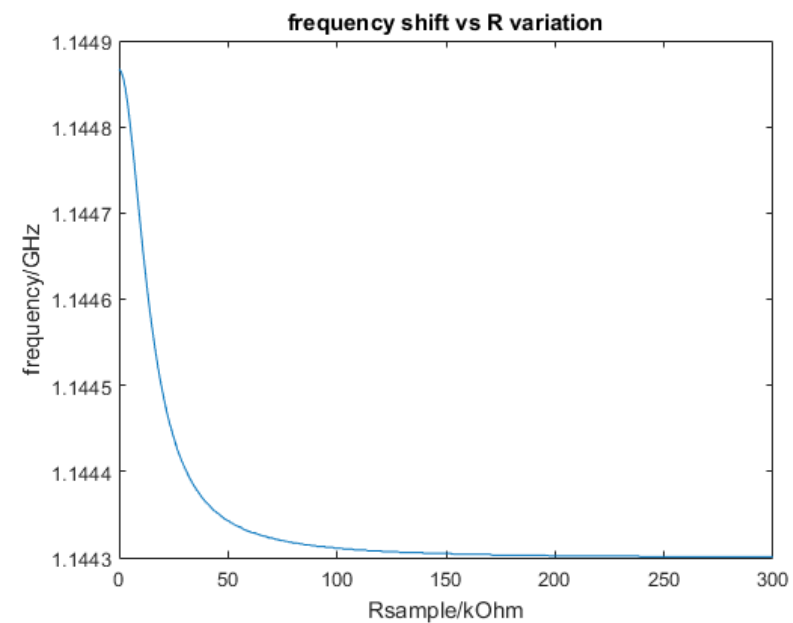
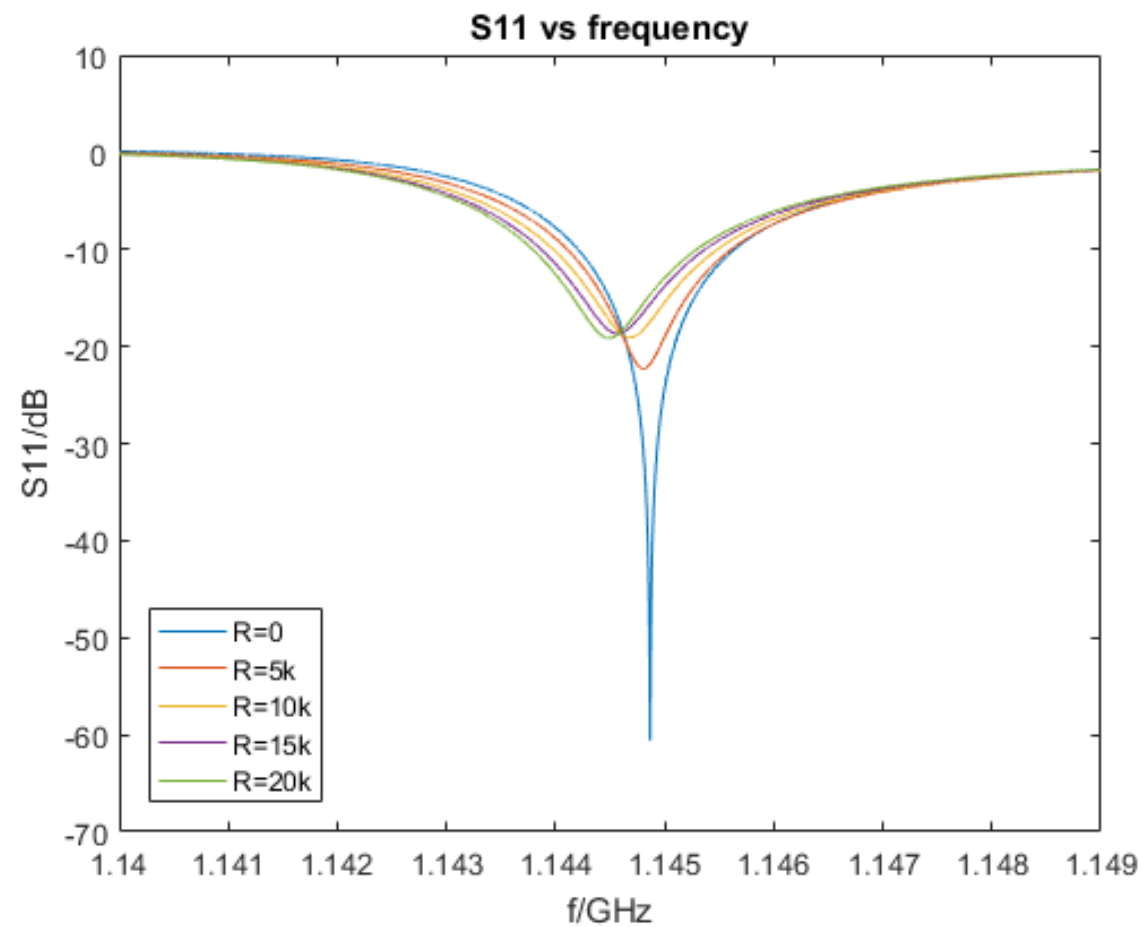




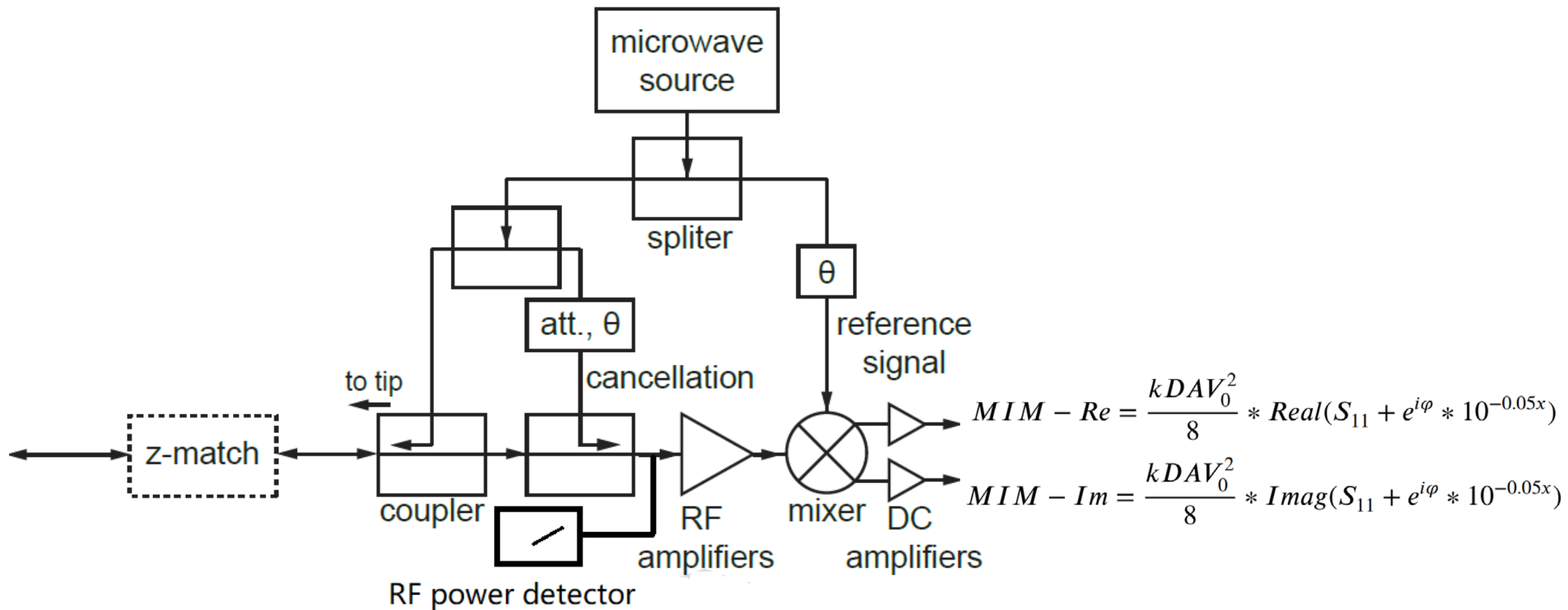
抵消后共振峰随样品电容的变化



抵消后共振峰随样品电阻的变化



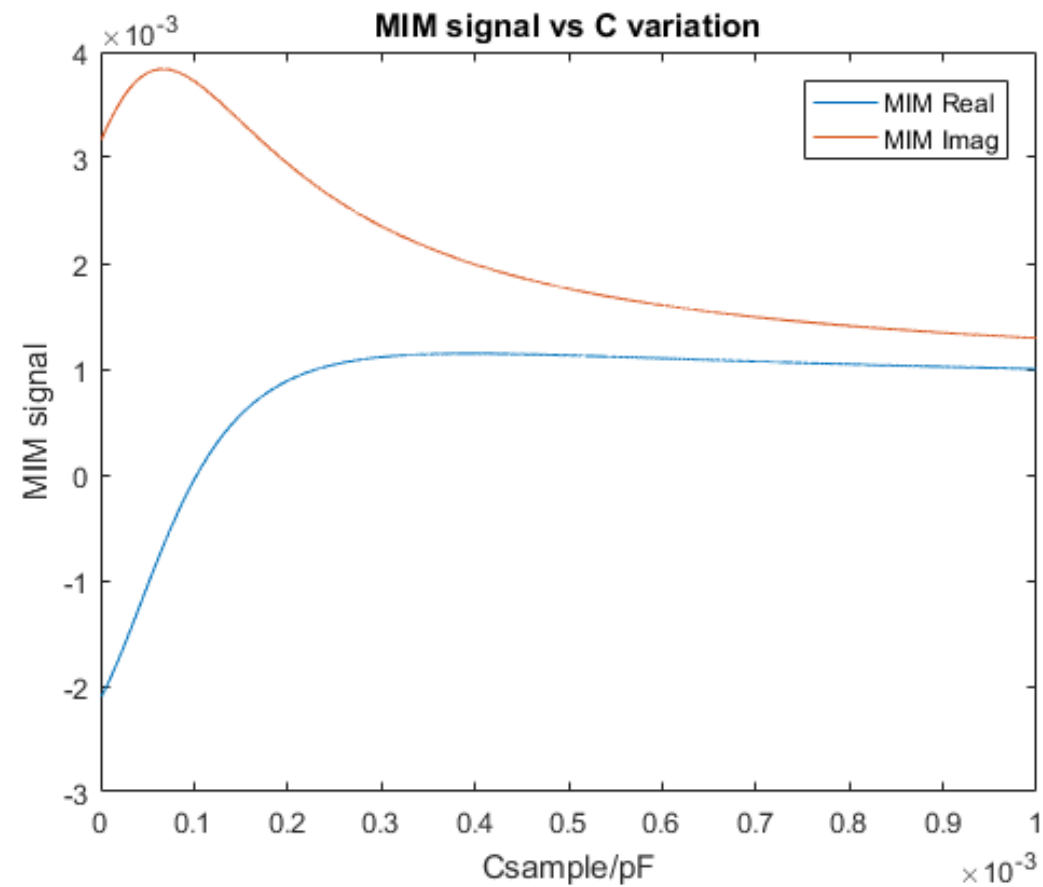
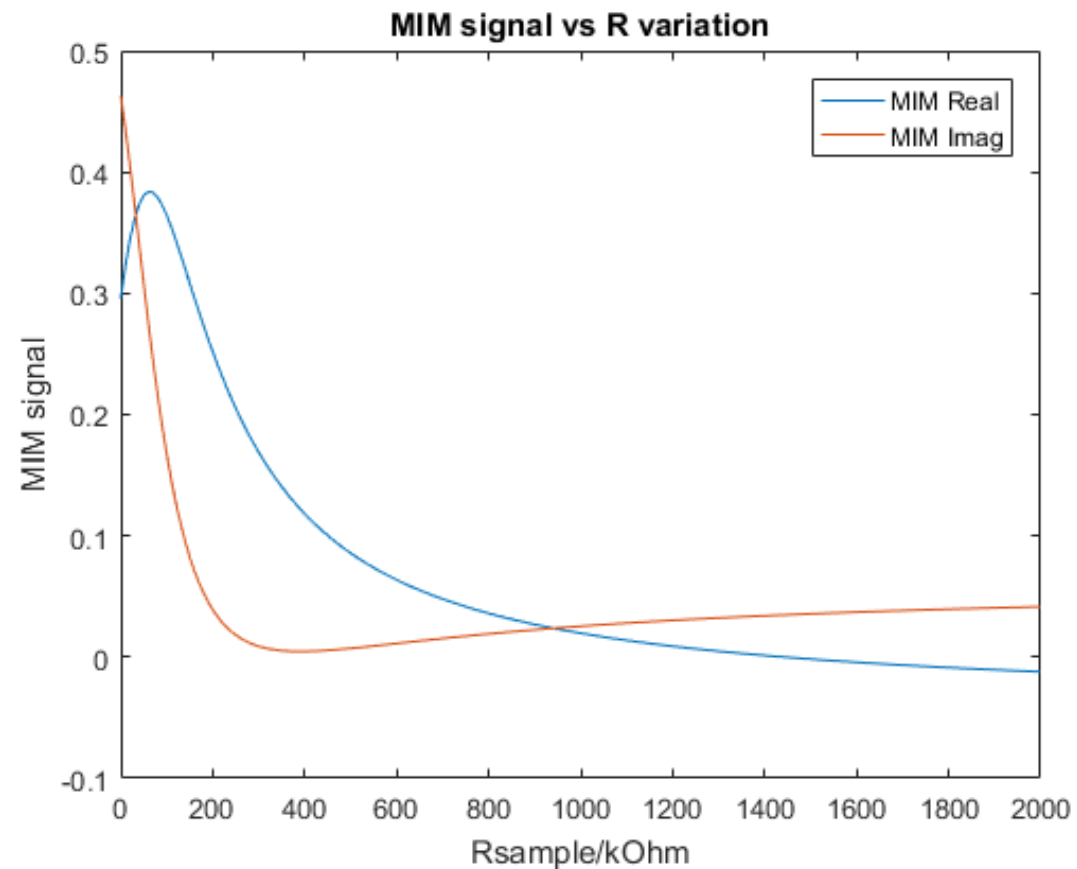
MIM 信号的计算



$$V_{total} = kA * V_{cancell} + V_{ref} = \frac{kAV_0}{4}(S_{11} + e^{i\varphi} * 10^{-0.05x})$$

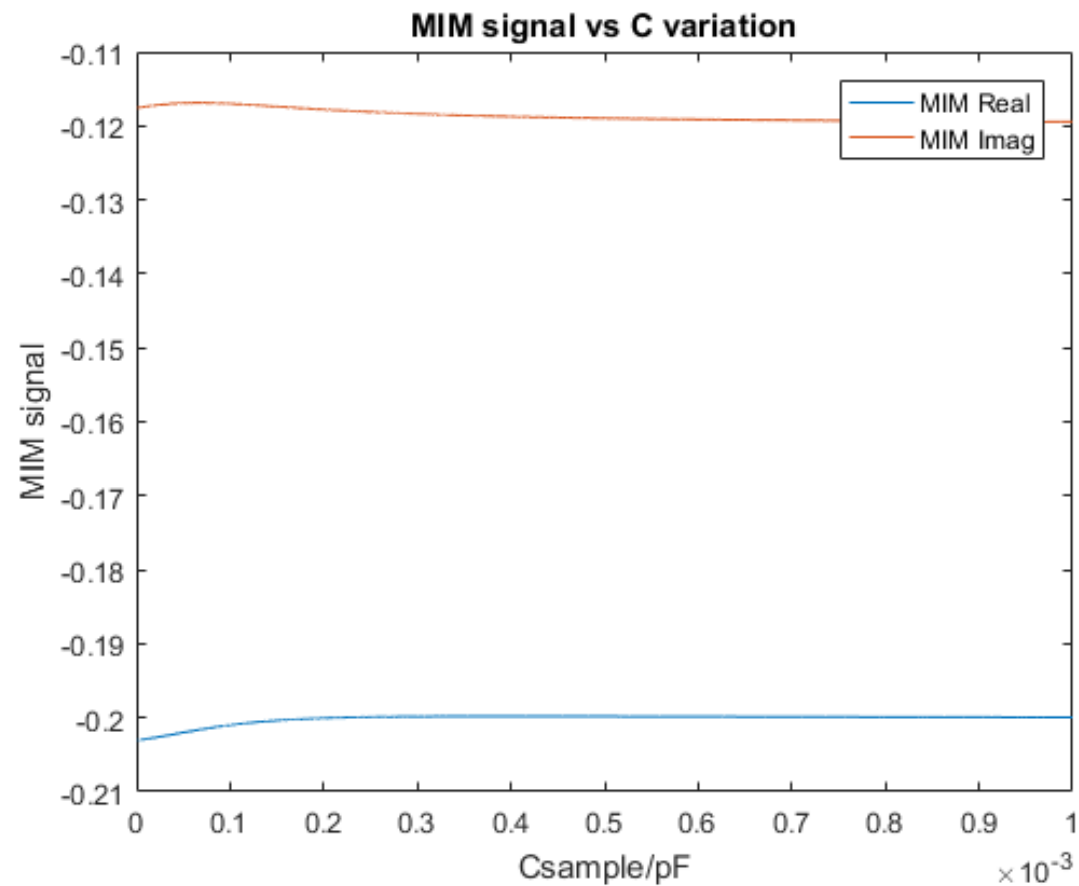
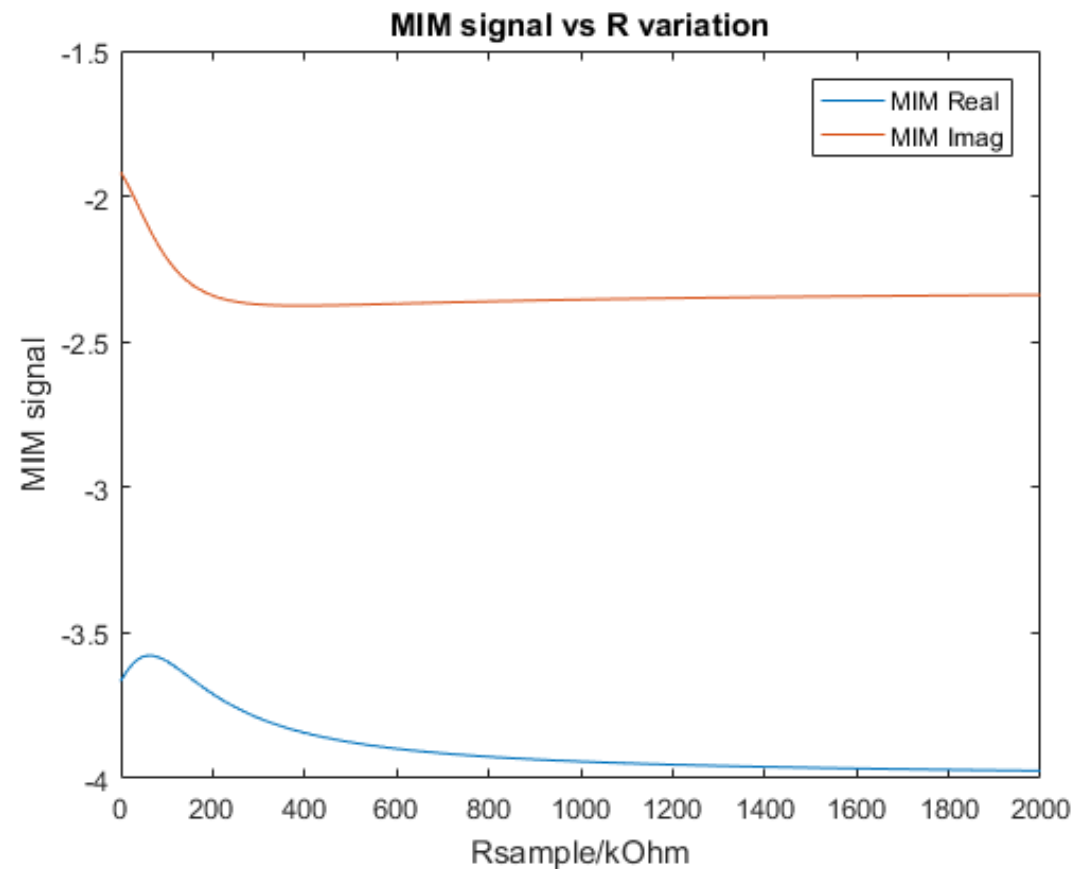


抵消后MIM 信号关于样品电阻、电容的变化图

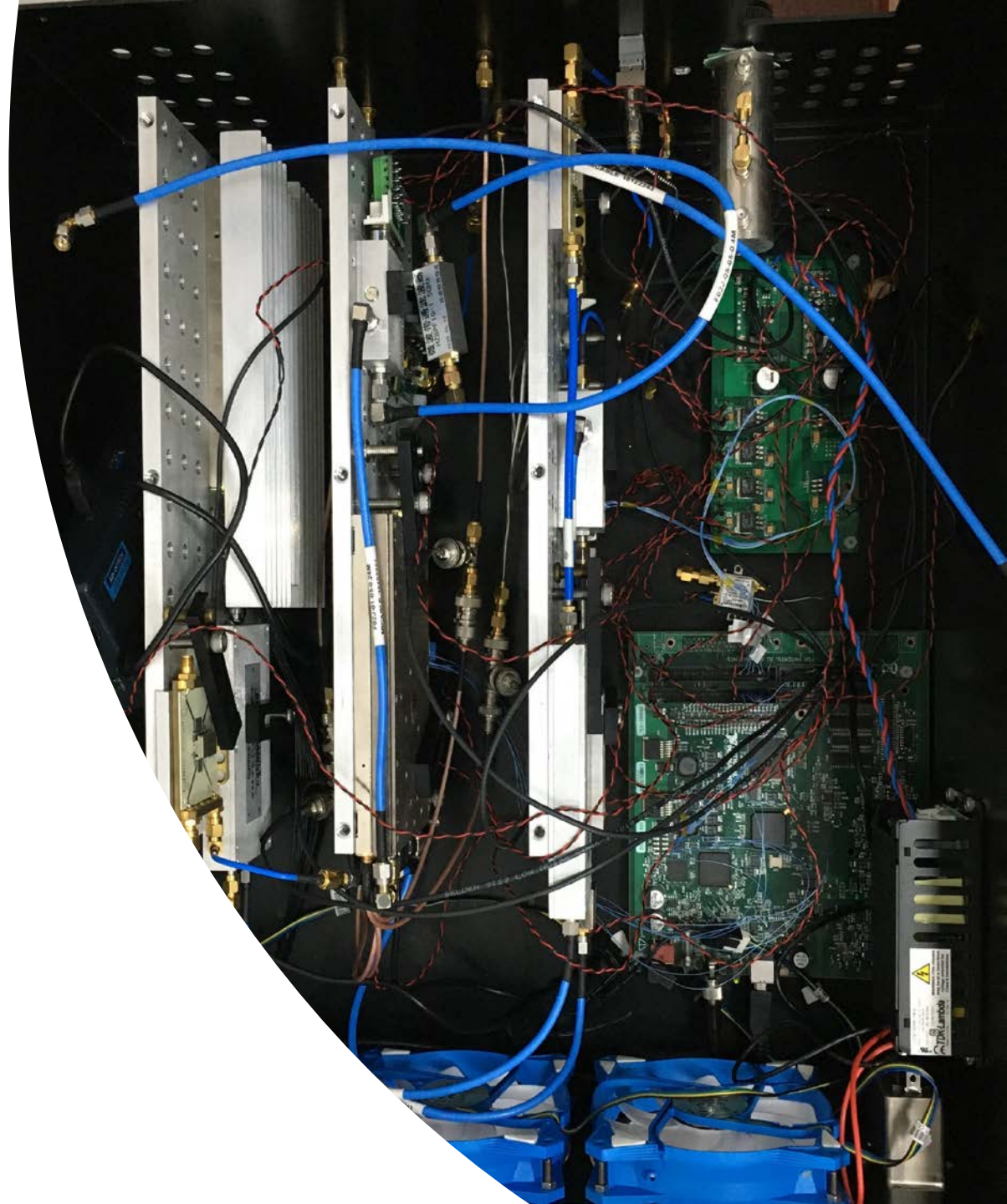




无抵消MIM 信号关于样品电阻、电容的变化图



- 微波电路基础
- 微波探测原理
- 微波阻抗显微系统





微波分辨原理

传播波 \longrightarrow 隐失波

- 实部虚部高对比度
- 非接触，非破坏
- 长波长，亚表面探测

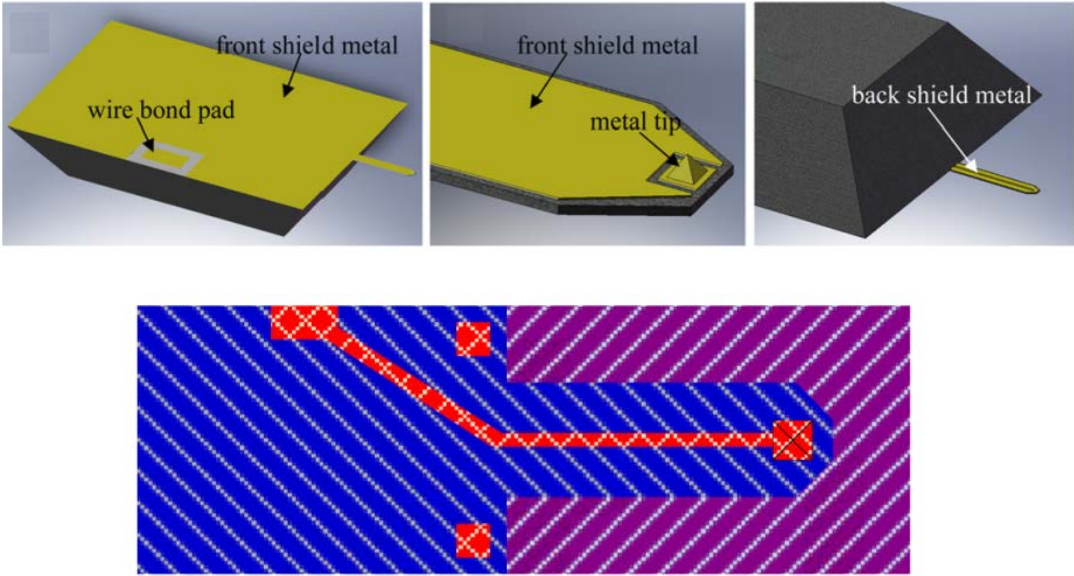
$$k_0^2 = \omega^2 \epsilon_0 (\epsilon' + \epsilon'') \mu$$

$$k_0^2 = \omega^2 \epsilon_0 (\epsilon' + i \frac{\sigma}{\omega \epsilon_0}) \mu$$

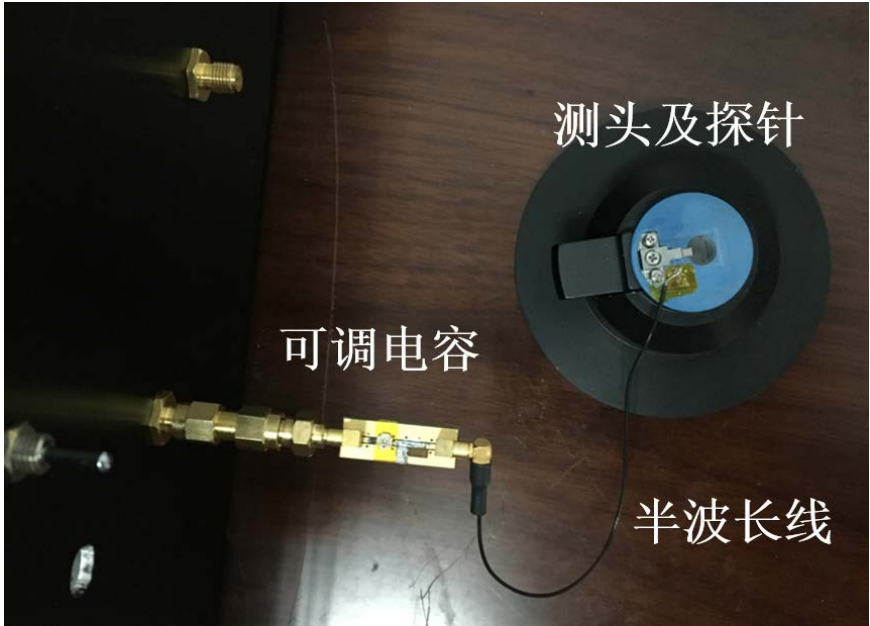
量子的 \longrightarrow 经典的



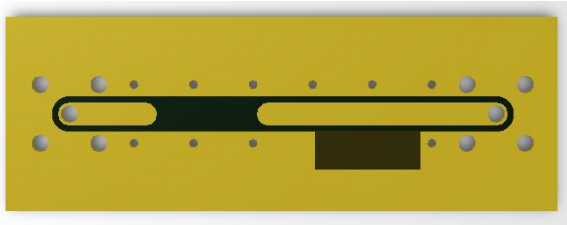
微波显微测头



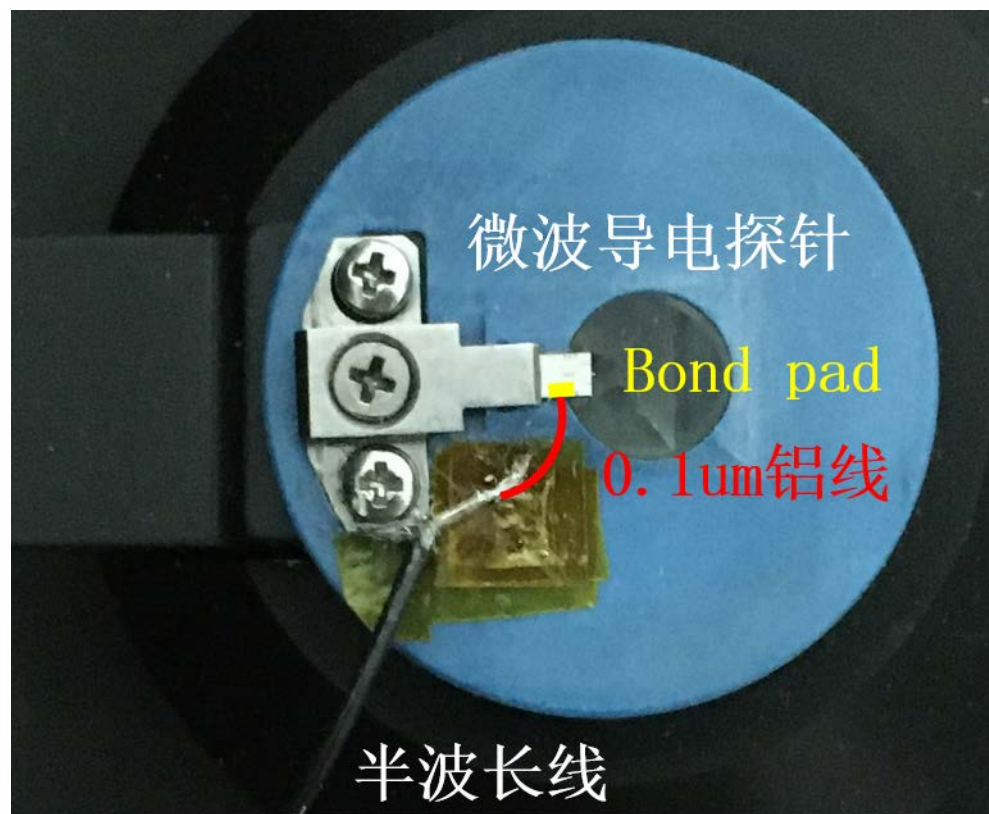
扫描微波导电探针 SMIM150-G5 示意图



共振匹配单元的实现

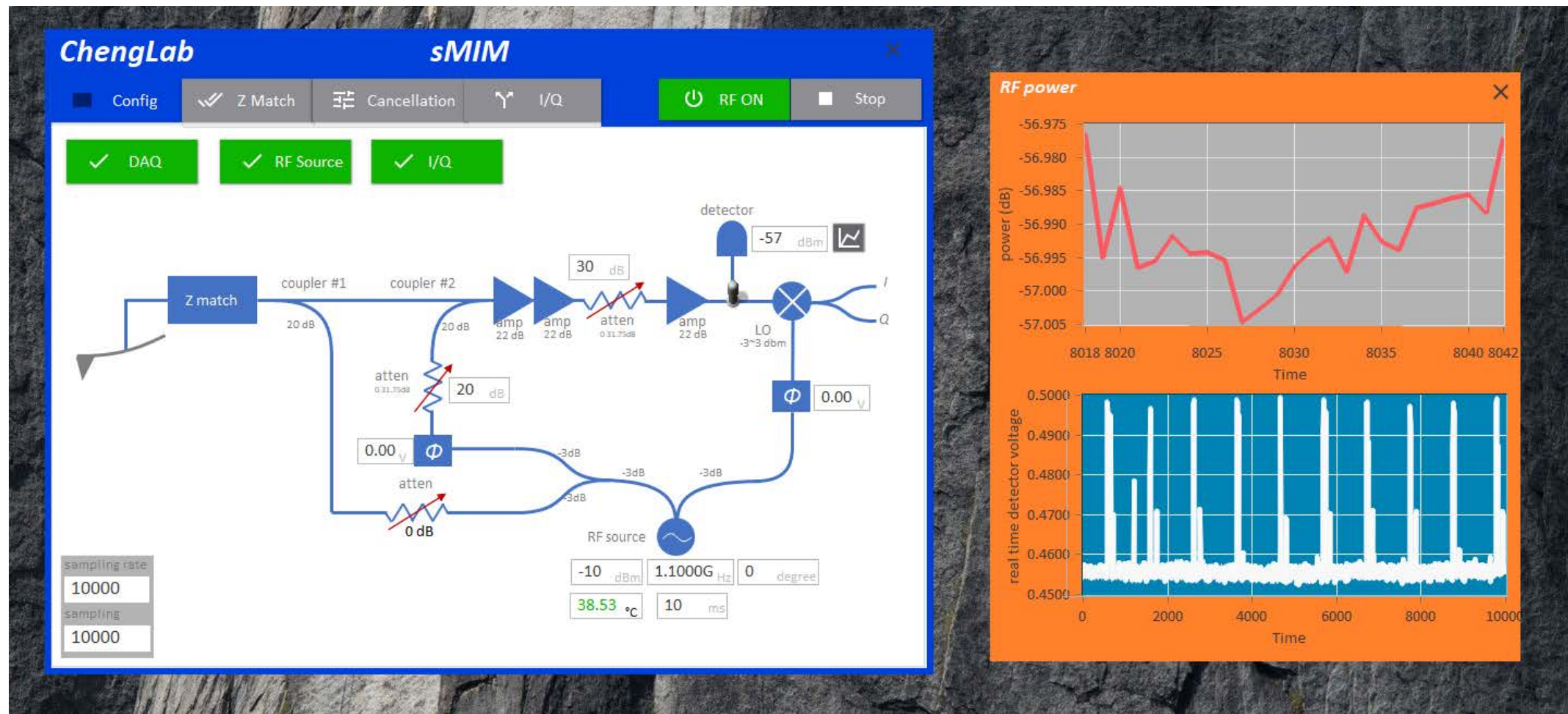


微波显微测头

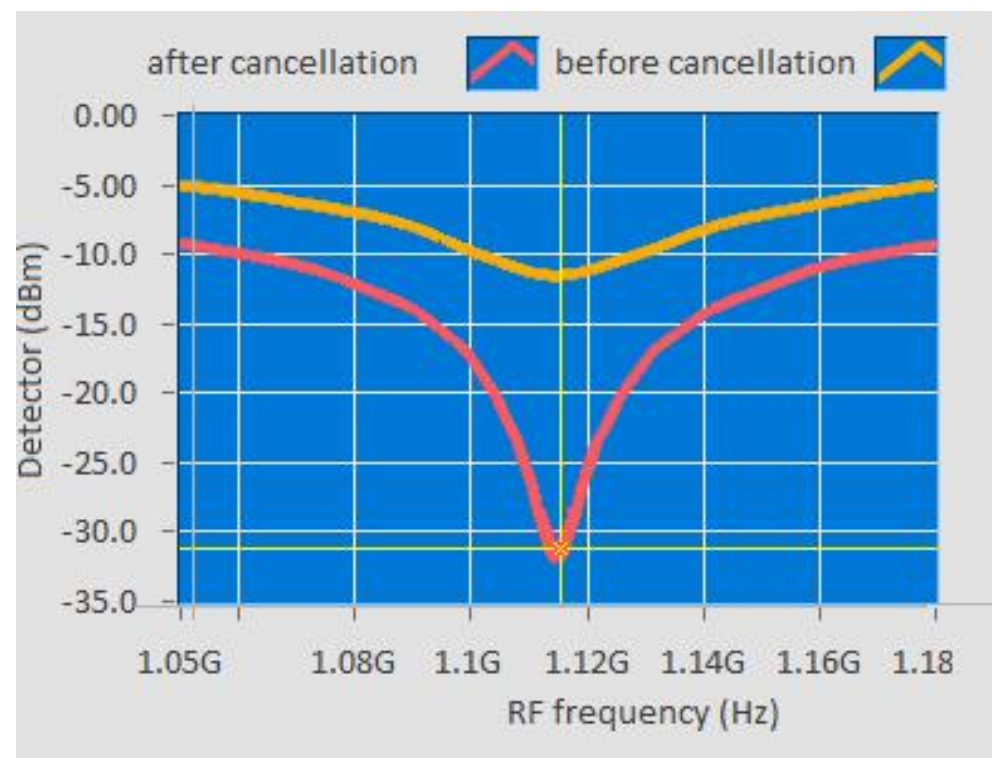
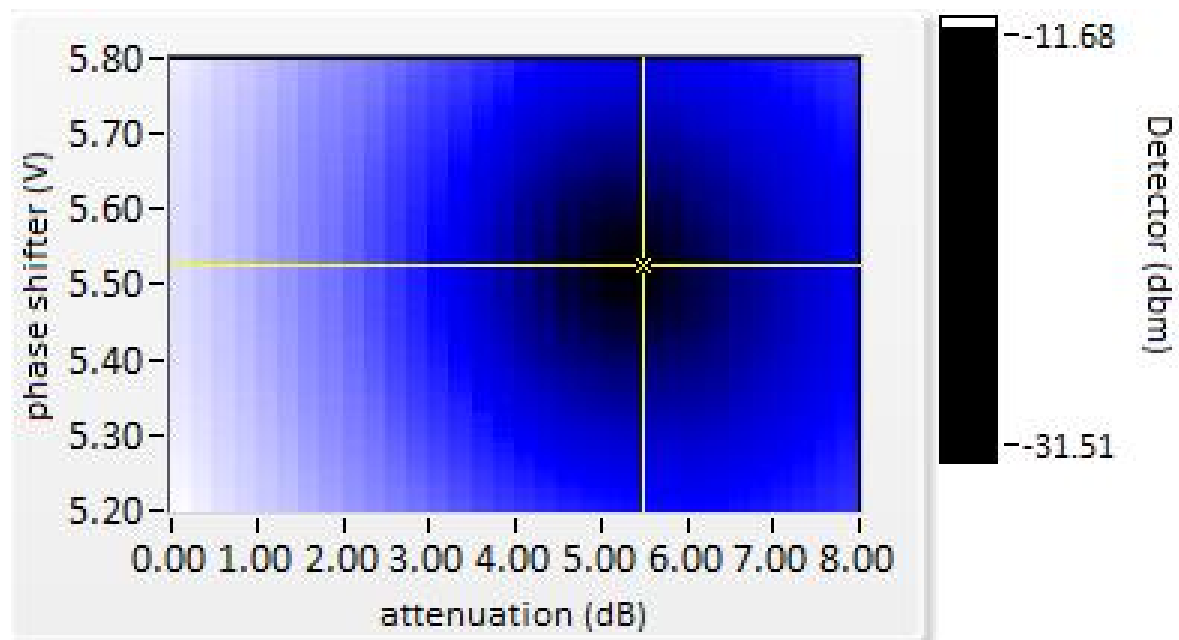


bond pad 直接连接至半波长线的内芯

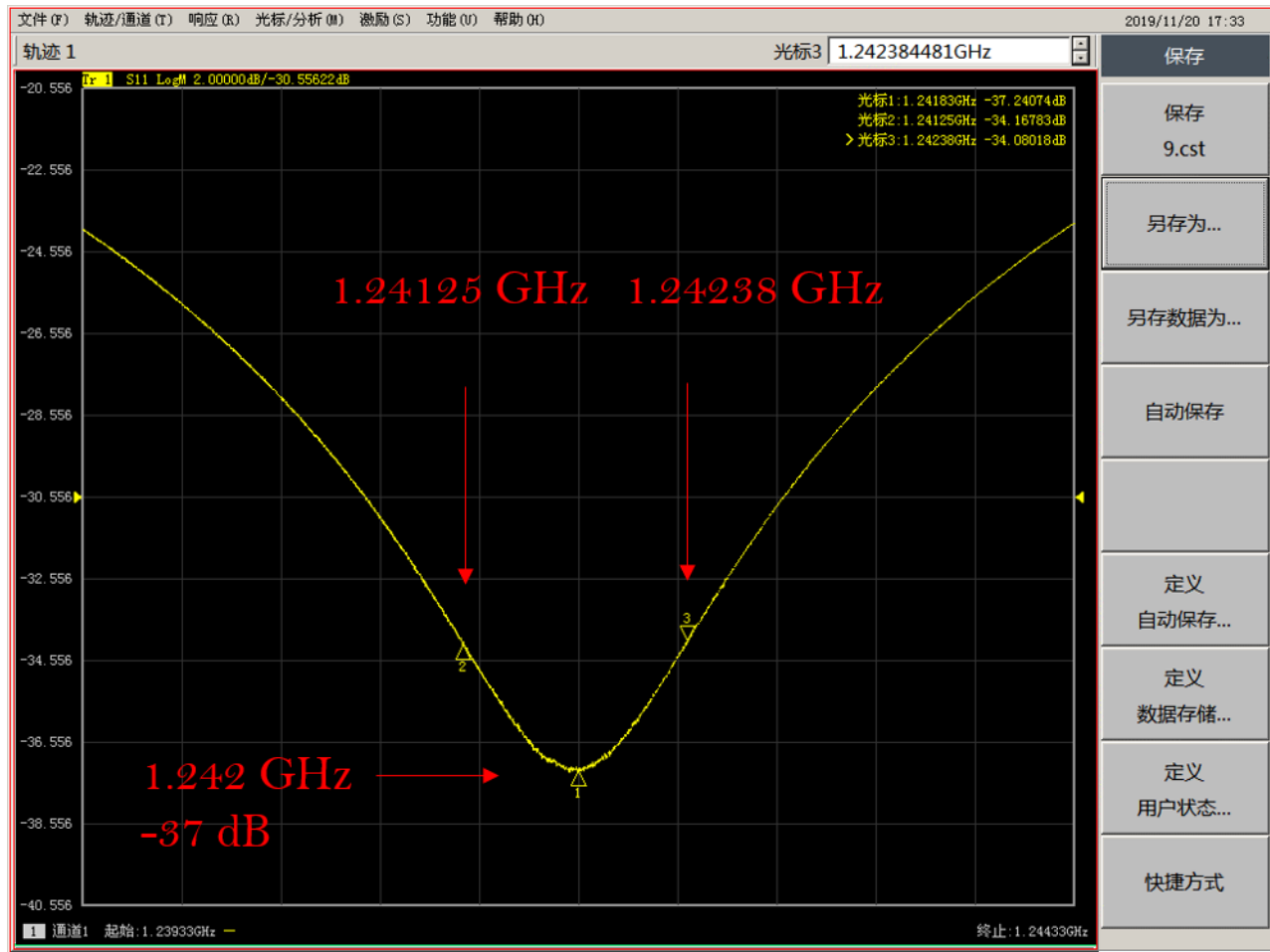
LabView控制程序界面



LabView控制抵消过程



实际测试共振匹配单元



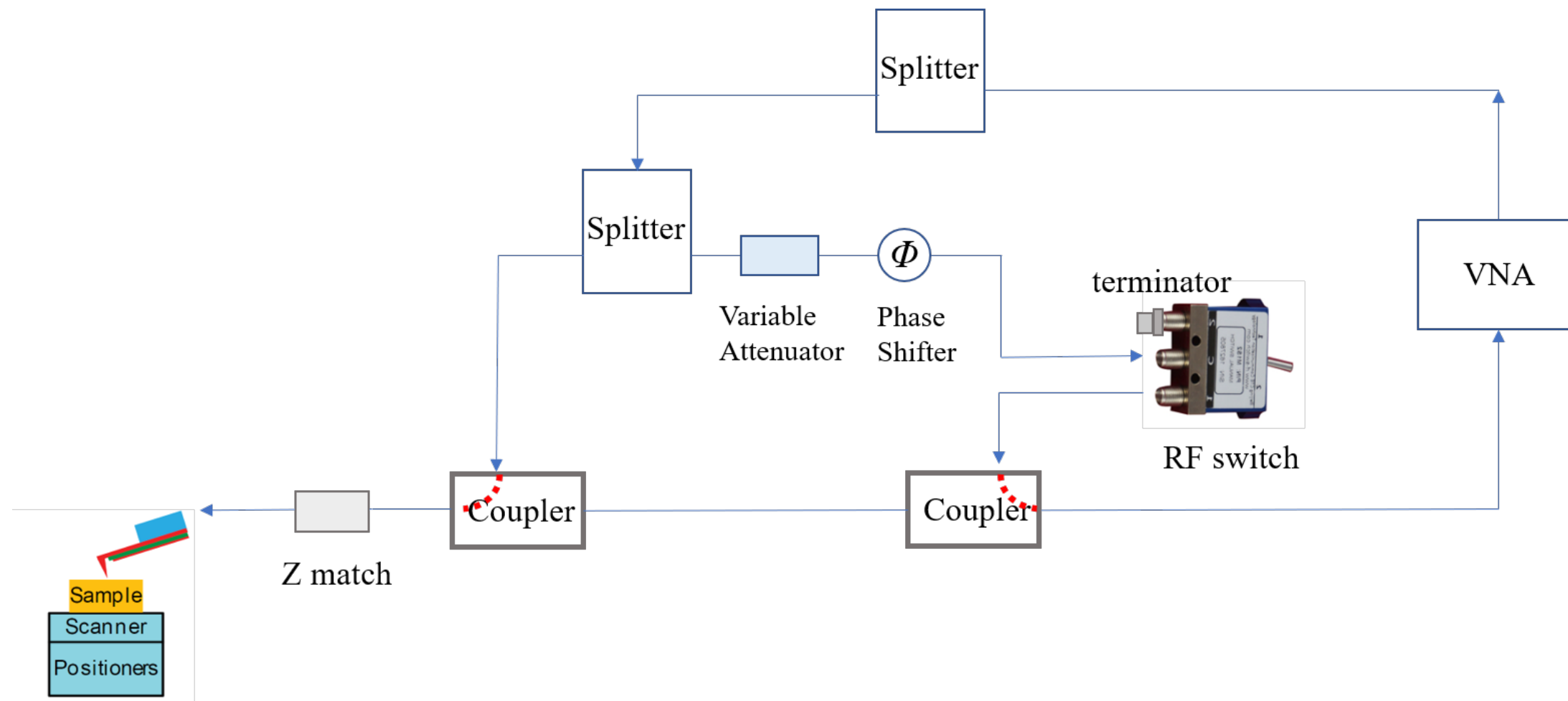
$$f = 1.242 \text{ GHz}$$

$$\Delta f = 1.13 \text{ MHz}$$

$$Q = f/\Delta f = 1100$$

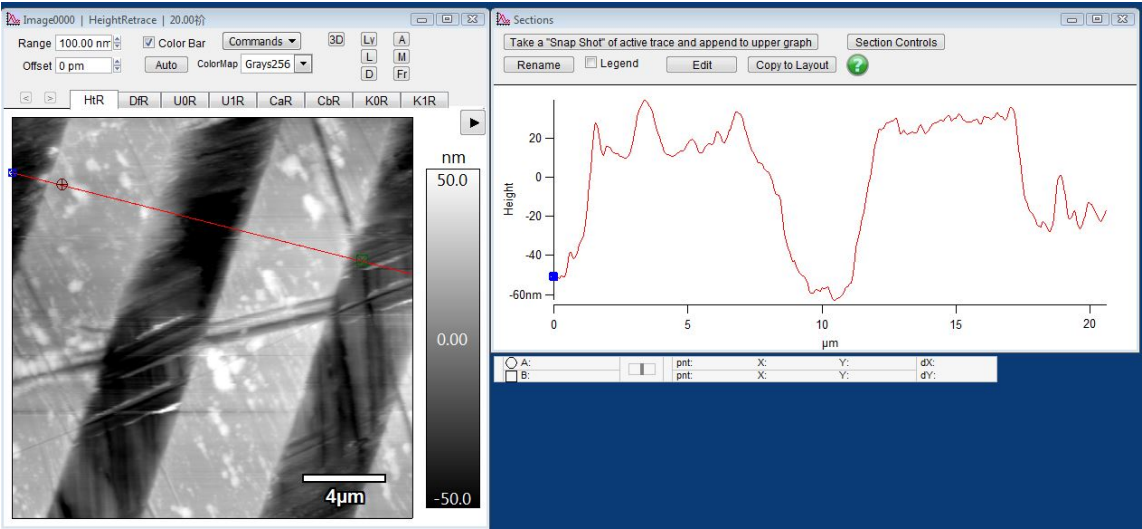


网络分析仪测试电路

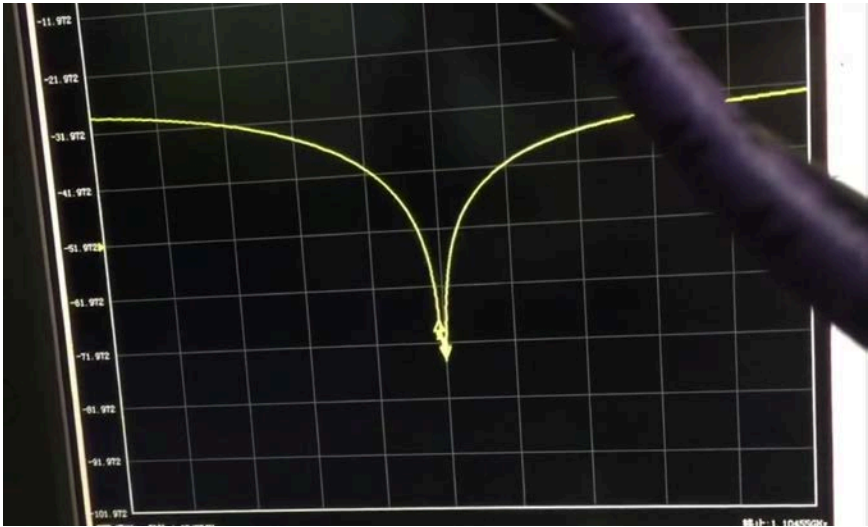




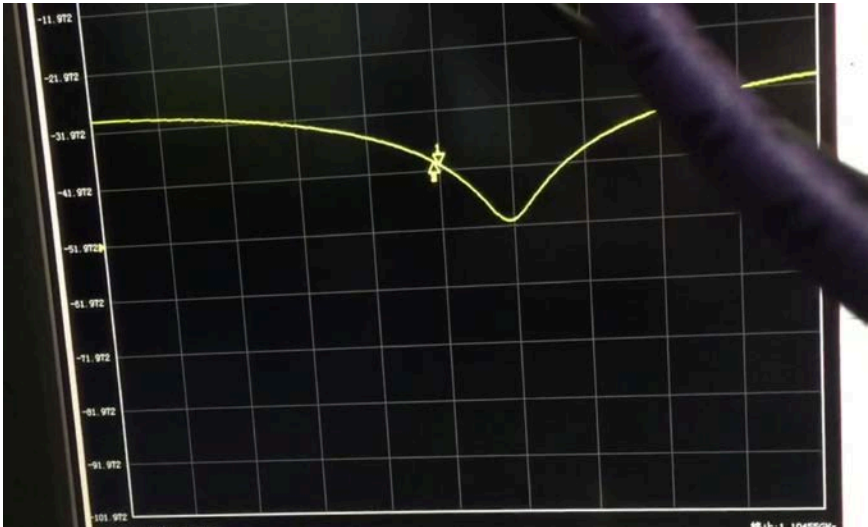
金属条带样品扫描



起伏约 50 nm

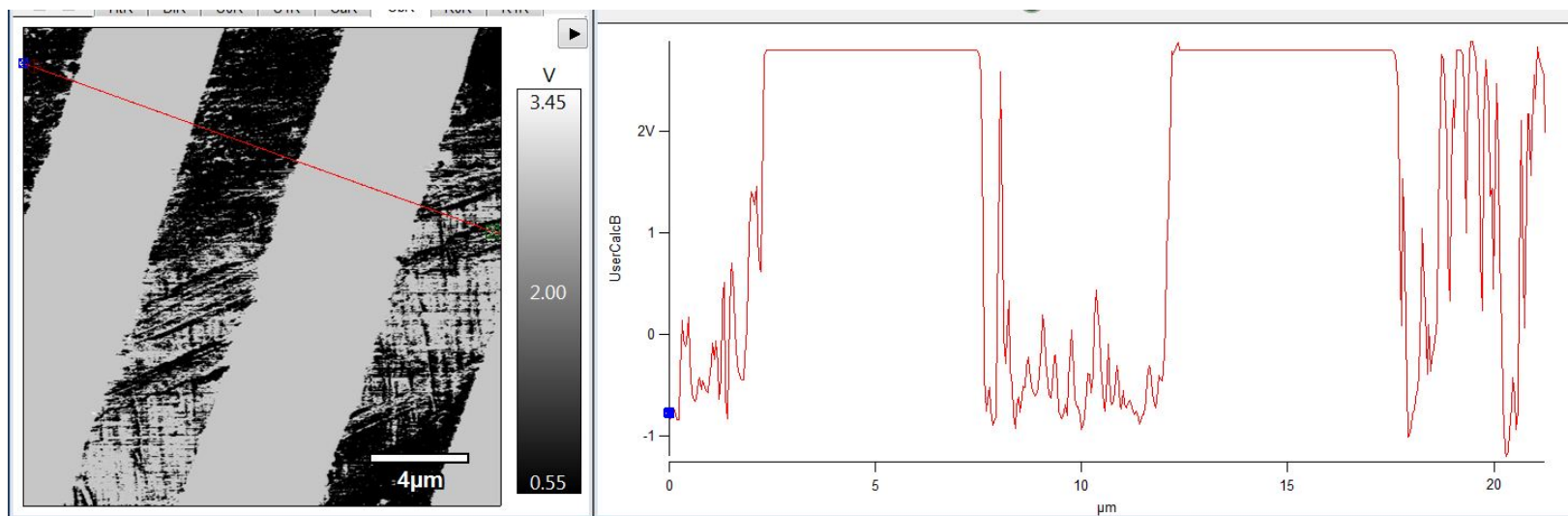
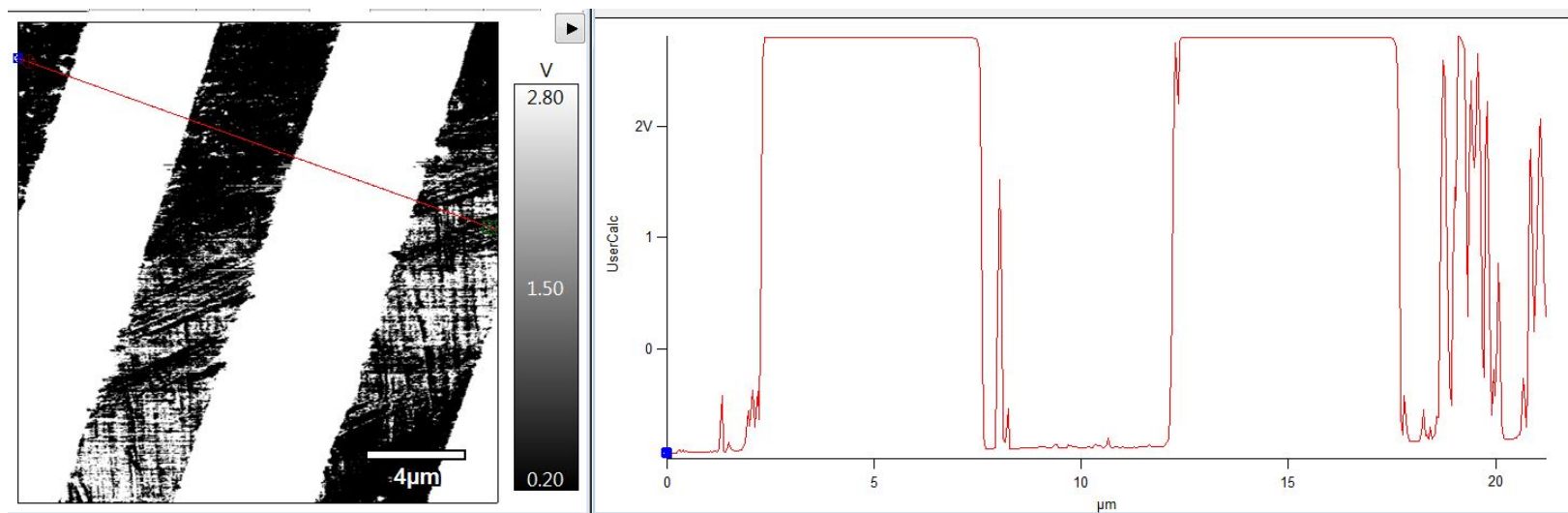


绝缘区域

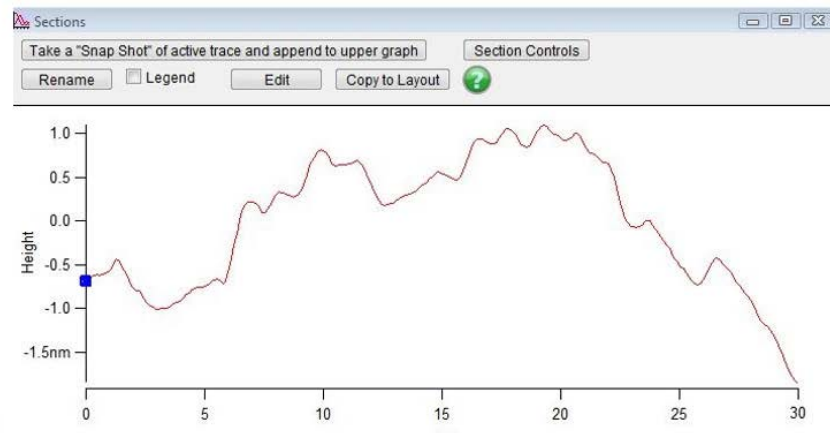
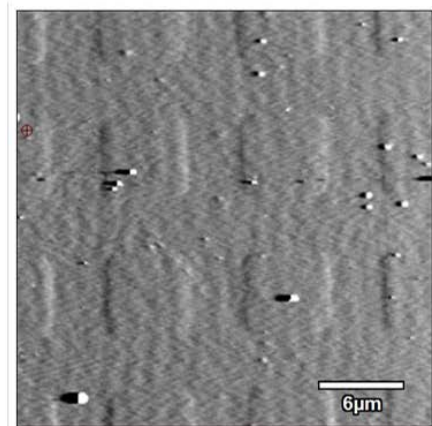


导电区域

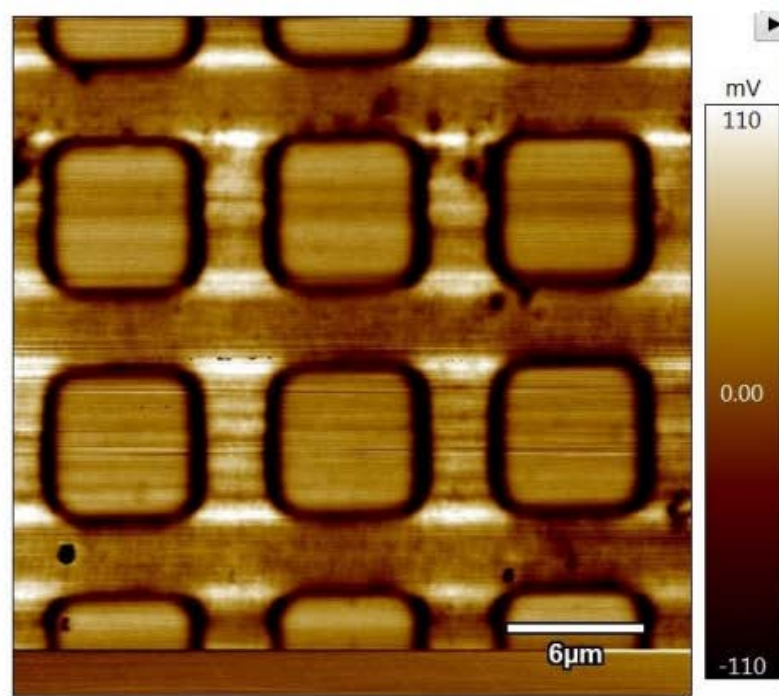
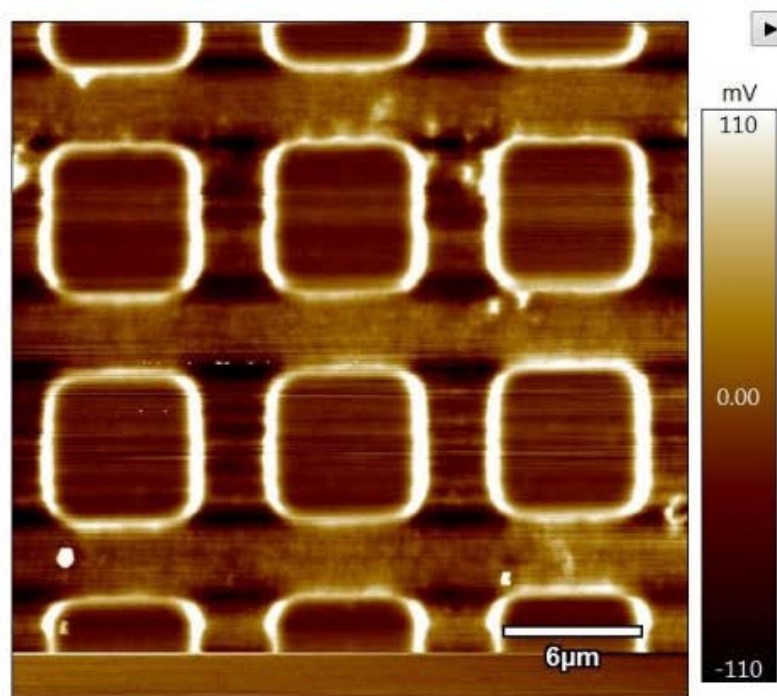
金属条带样品扫描



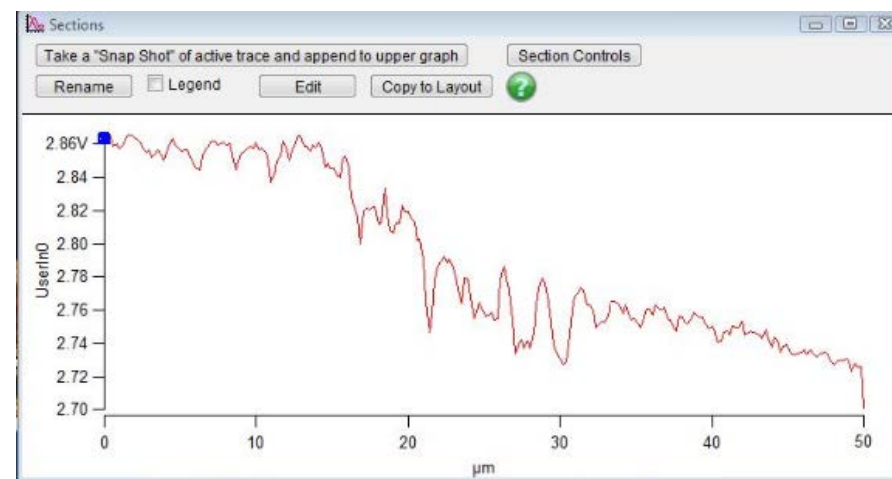
硅掺杂样品扫描



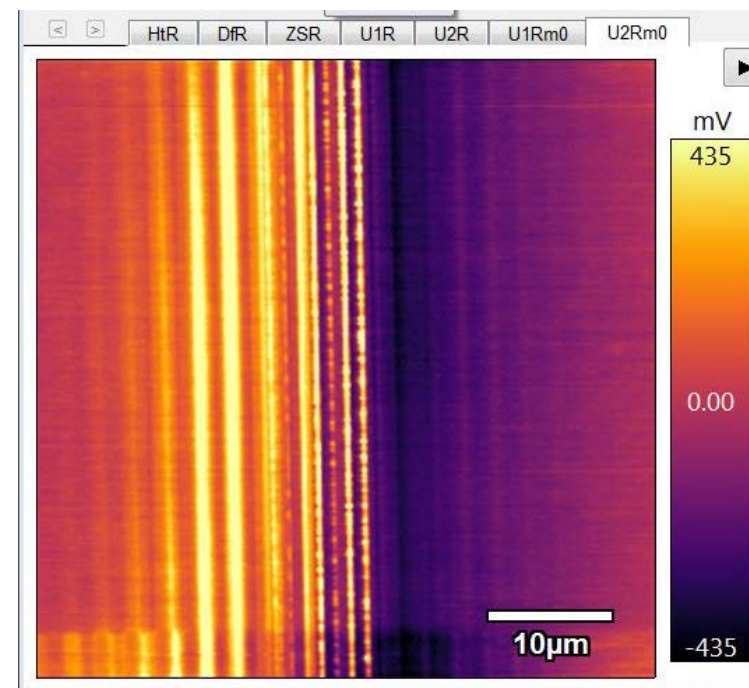
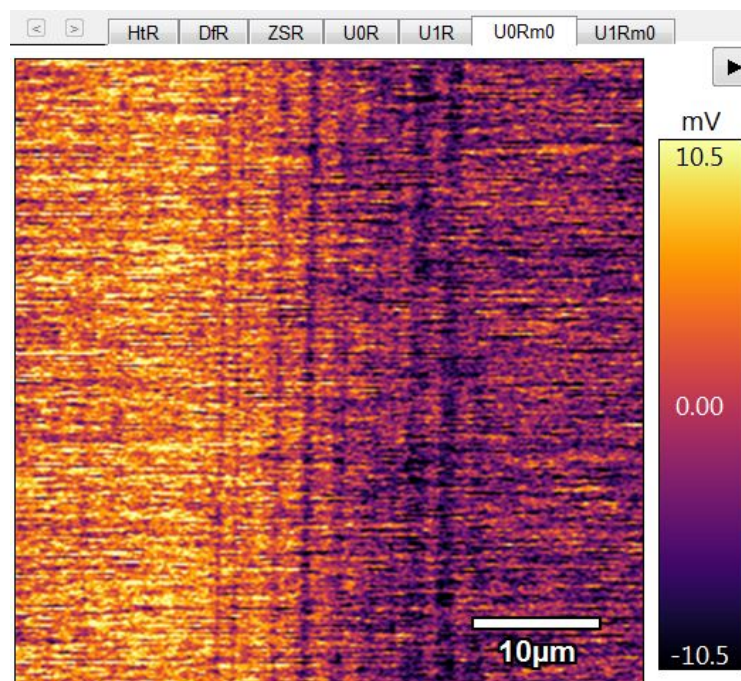
起伏约2 nm



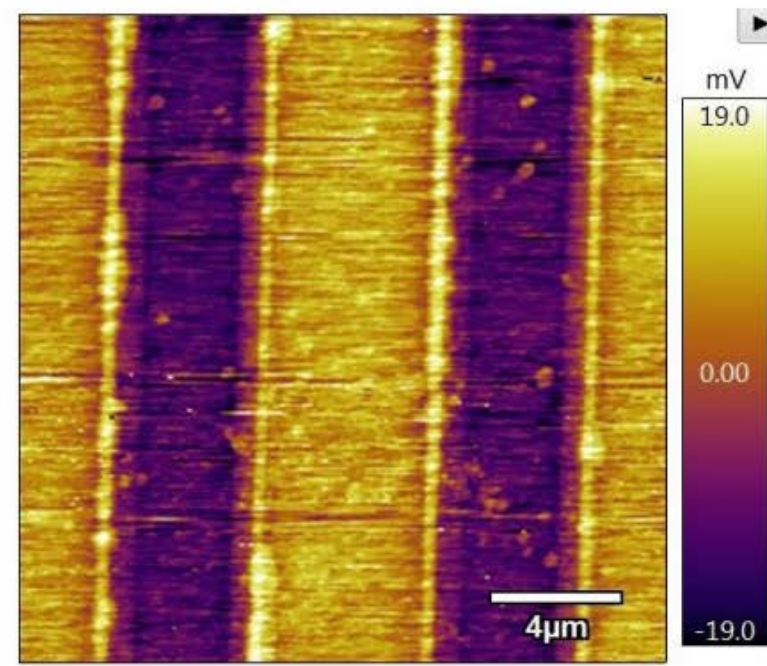
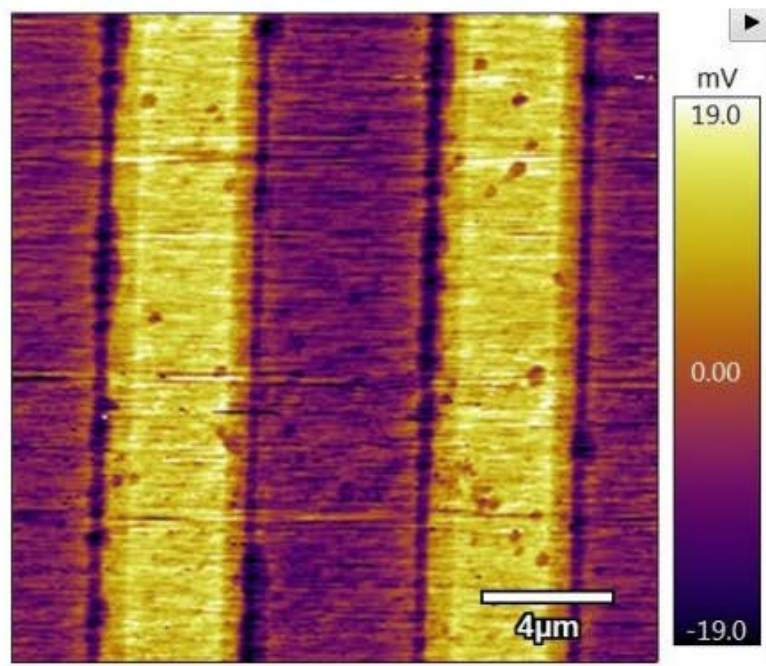
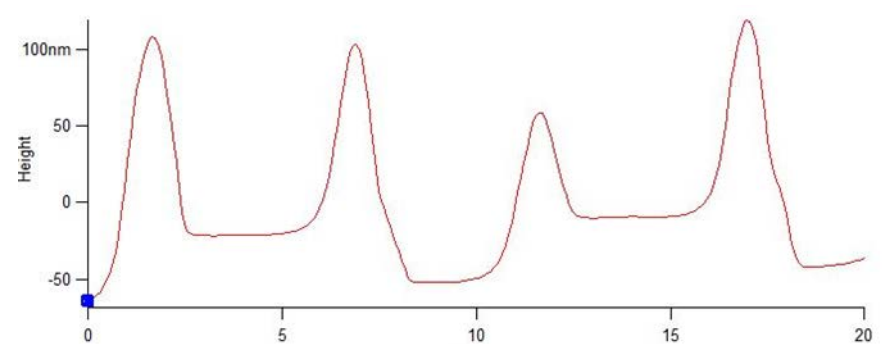
IFX掺杂样品扫描



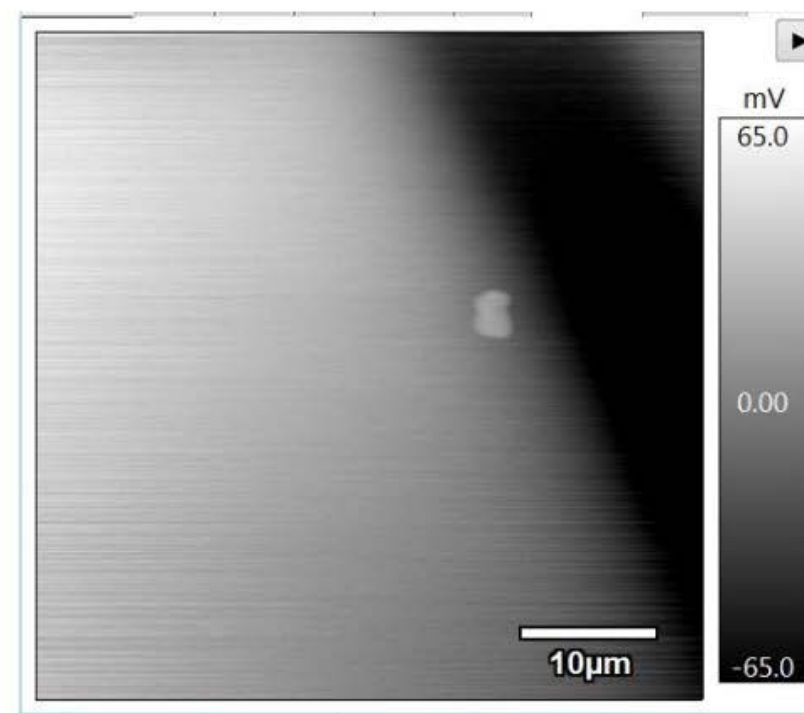
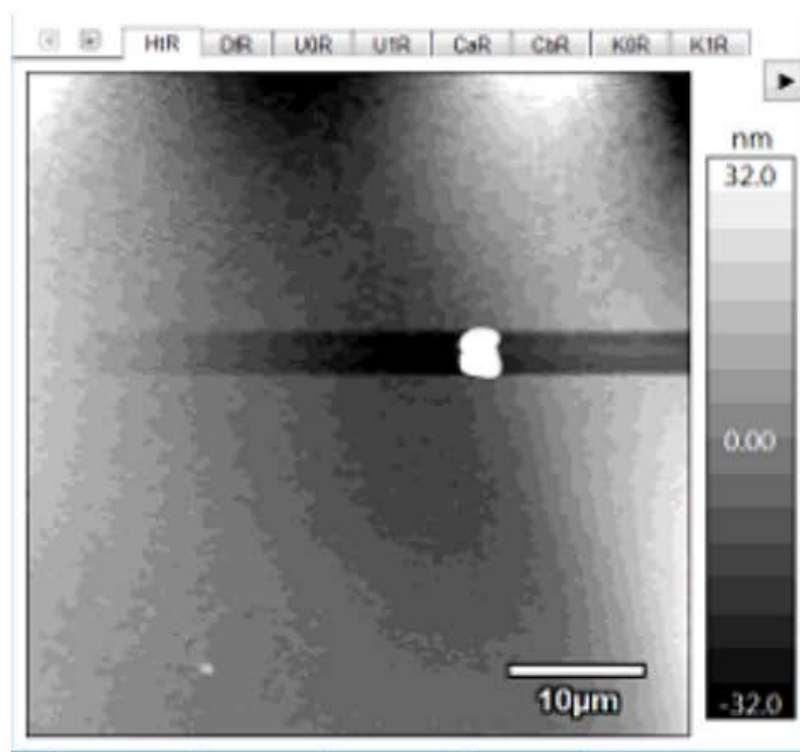
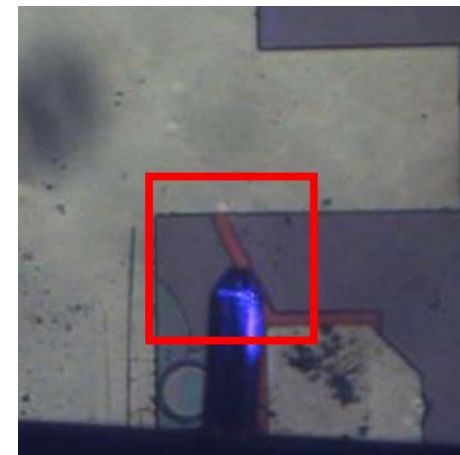
信号截面



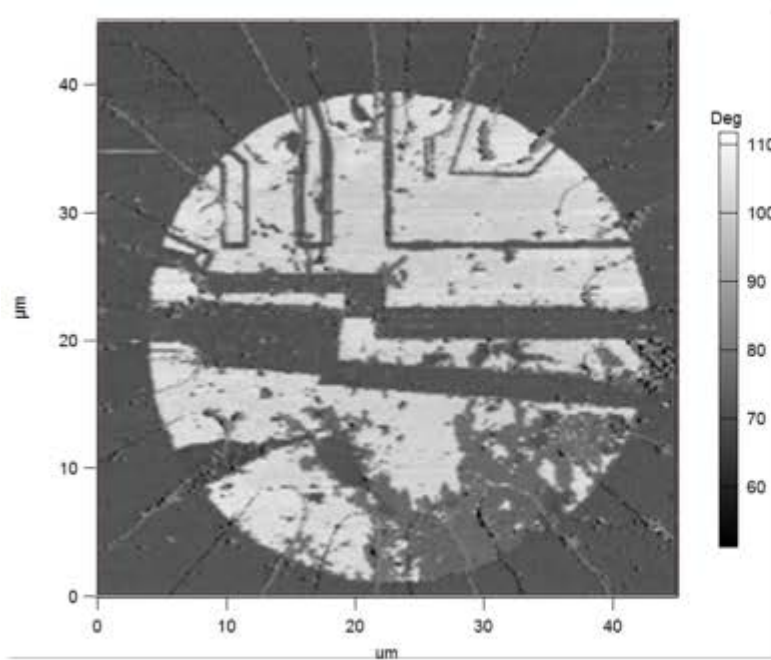
埋在绝缘体下方的金属条带样品扫描



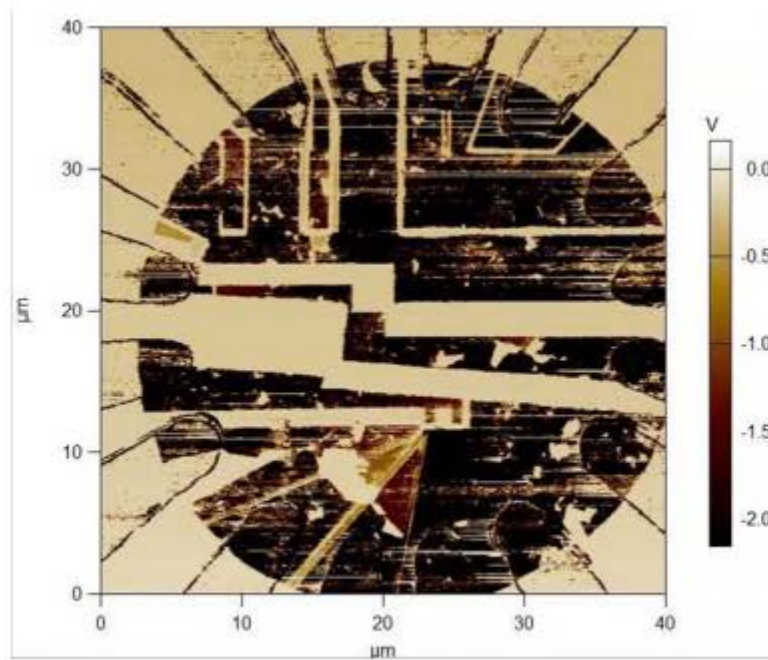
氮化硅下方的 Pt 对应 MIM 扫描信号



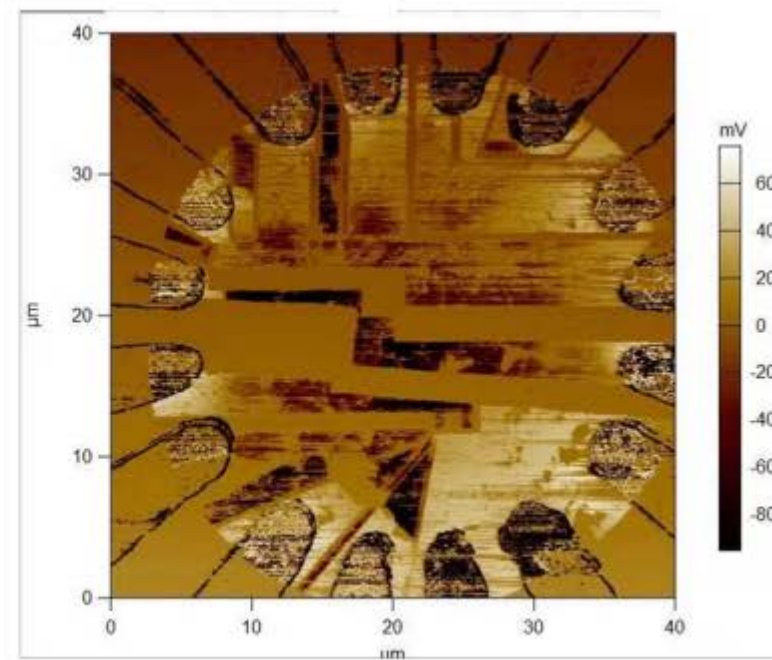
扫描单层导电石墨烯图像



topography



MIM I channel



MIM Q channel

扫描 $\text{LaAlO}_3/\text{SrTiO}_3$ 界面处导电纳米线的图像

