EM 2D Design Project

Group 5

Members:
Li Jiang Yan (1003693)
Lim Yun Kai Clara (1003629)
Loh Zhi Xuan (1003389)
Low Wei Kang (1003472)

Contents

Problem Statement

Goal

To develop a non-invasive method to detect one's hydration level

Problems with current methods

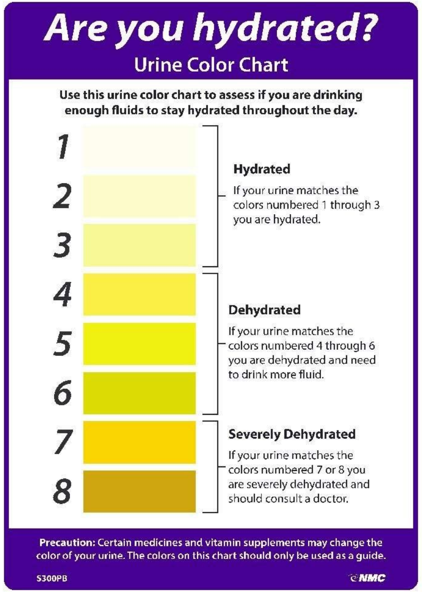
- Blood test: invasive to body and lab tests take time
- Urine: increase in urine color intensity occurs in late stages of thirst reaction; inaccurate

What does it mean to be ‘hydrated’?

Conventional advice: pale urine and/or wet mouth

In reality: urine only becomes more yellow and mouth becomes drier at the later stages of the thirst reaction (due to dehydration)

Clinical: when the concentration of salt (mostly NaCl) in the blood becomes higher or equal to 0.145 mmol dm^{-3}, the person is considered dehydrated



[NaCl] / mmol dm^{-3} ≤ 0.135 overhydration hyponatremia	0.135 < [NaCl] / mmol dm^{-3} < 0.145 hydrated normonatremia	[NaCl] / mmol dm^{-3} ≥ 0.145 dehydrated hypernatremia

Electromagnetic properties of salt solution

Permittivity of salt solution: decreases as the concentration of NaCl in salt solution increases

$$\varepsilon_r = \varepsilon_w - \alpha\,[\mathsf{NaCl}],\ \alpha = 11.7\ \mathsf{dm}^3\ \mathsf{mol}^{-1},\ \varepsilon_w = 78.3$$

Permeability of salt solution: independent on the concentration of NaCl

Conductivity of salt solution: increases as the concentration of NaCl in salt solution increases

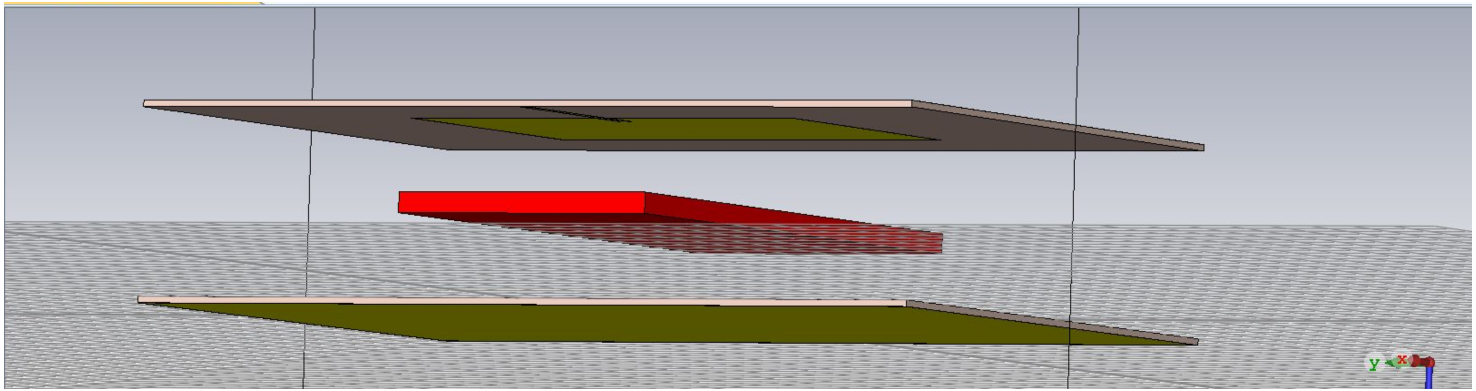
$$\sigma = 0.1673\,[\mathsf{NaCl}] + 2.3381$$

Methodology

The wrist of the person is in between a pair of rectangular microstrip patch antennas.

The rectangular patch is designed to resonate at a desired resonant frequency.

Blood patch: height of vein diameter = 2.3 mm, width of wrist = 60 mm



Rectangular microstrip patch antenna

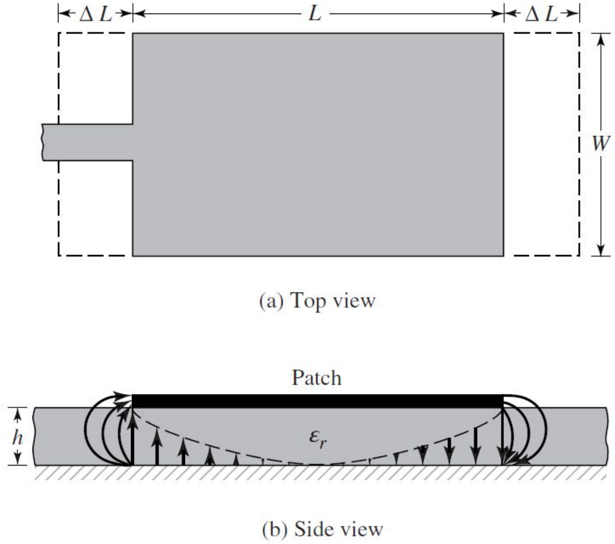


Figure 14.7 Physical and effective lengths of rectangular microstrip patch.

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}$$

We directly used these measurements for our intended microstrip antenna (such that it resonates at an intended frequency).

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2}$$

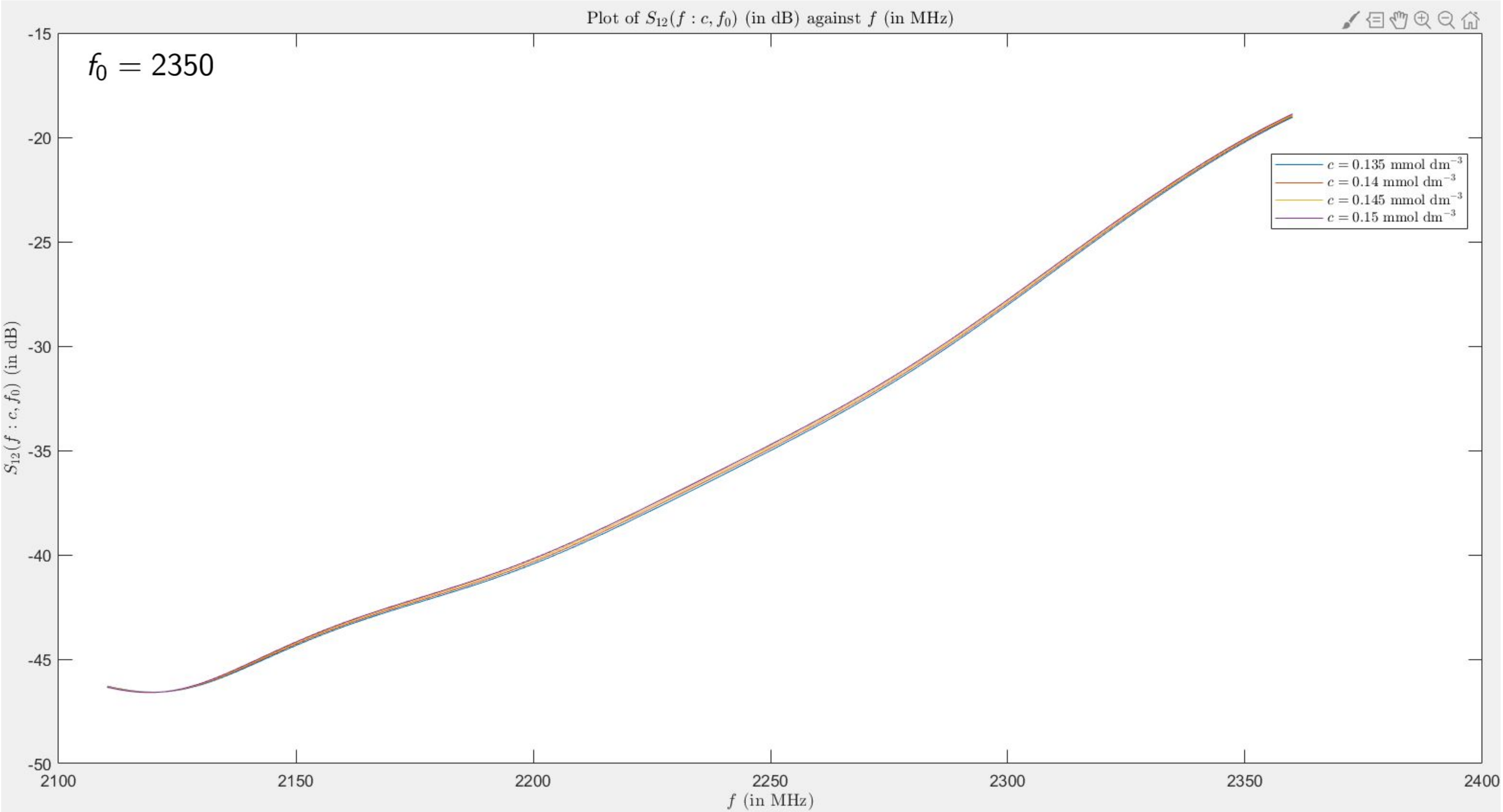
$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff}+0.3)\left[\frac{W}{h}+0.264\right]}{(\varepsilon_{reff}-0.258)\left[\frac{W}{h}+0.8\right]}$$

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{\mathrm{reff}}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L$$

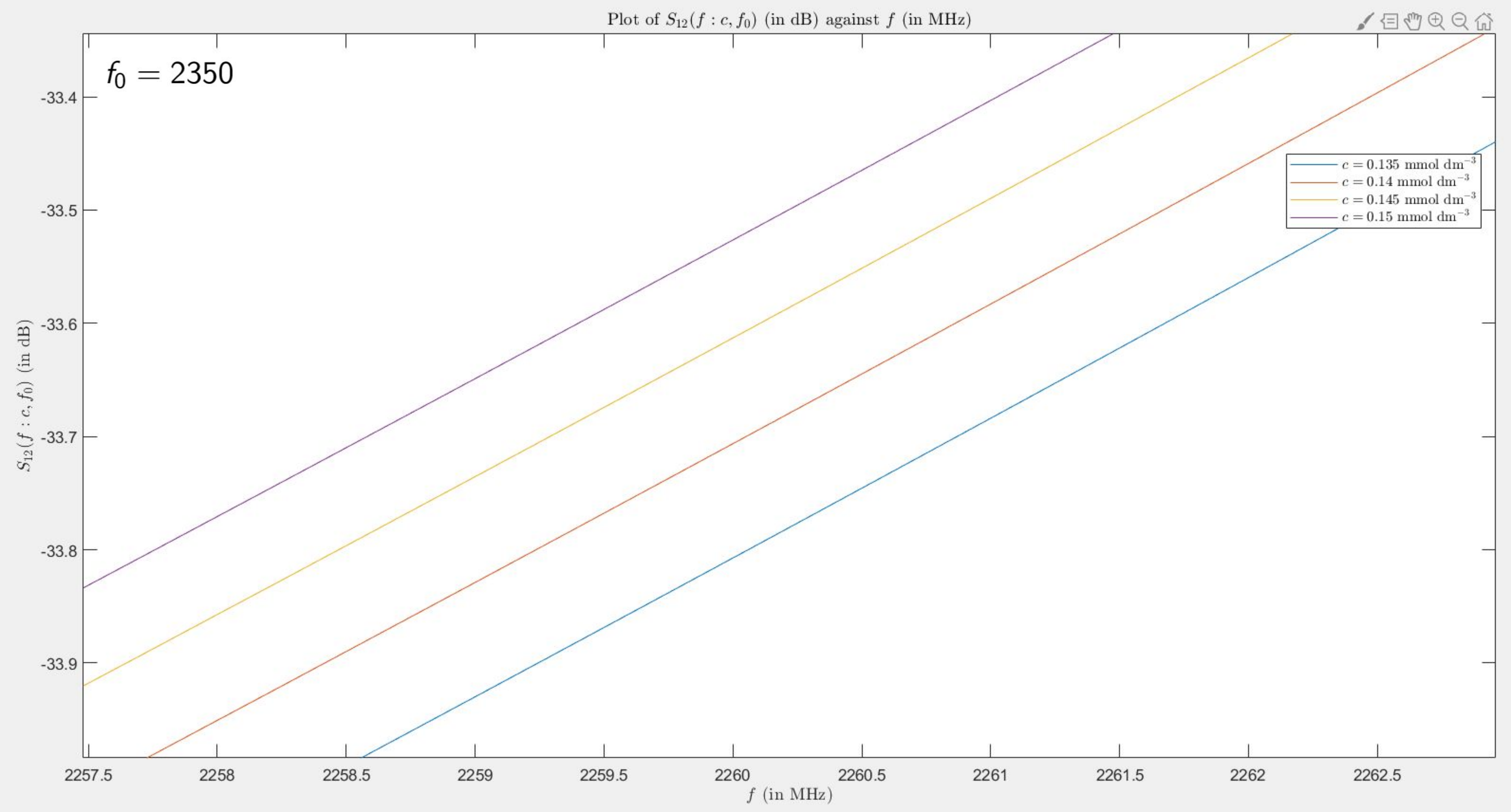
Notation

$S\,(f : c, f_0)$: S parameter, function of variable f with parameters c and f_0

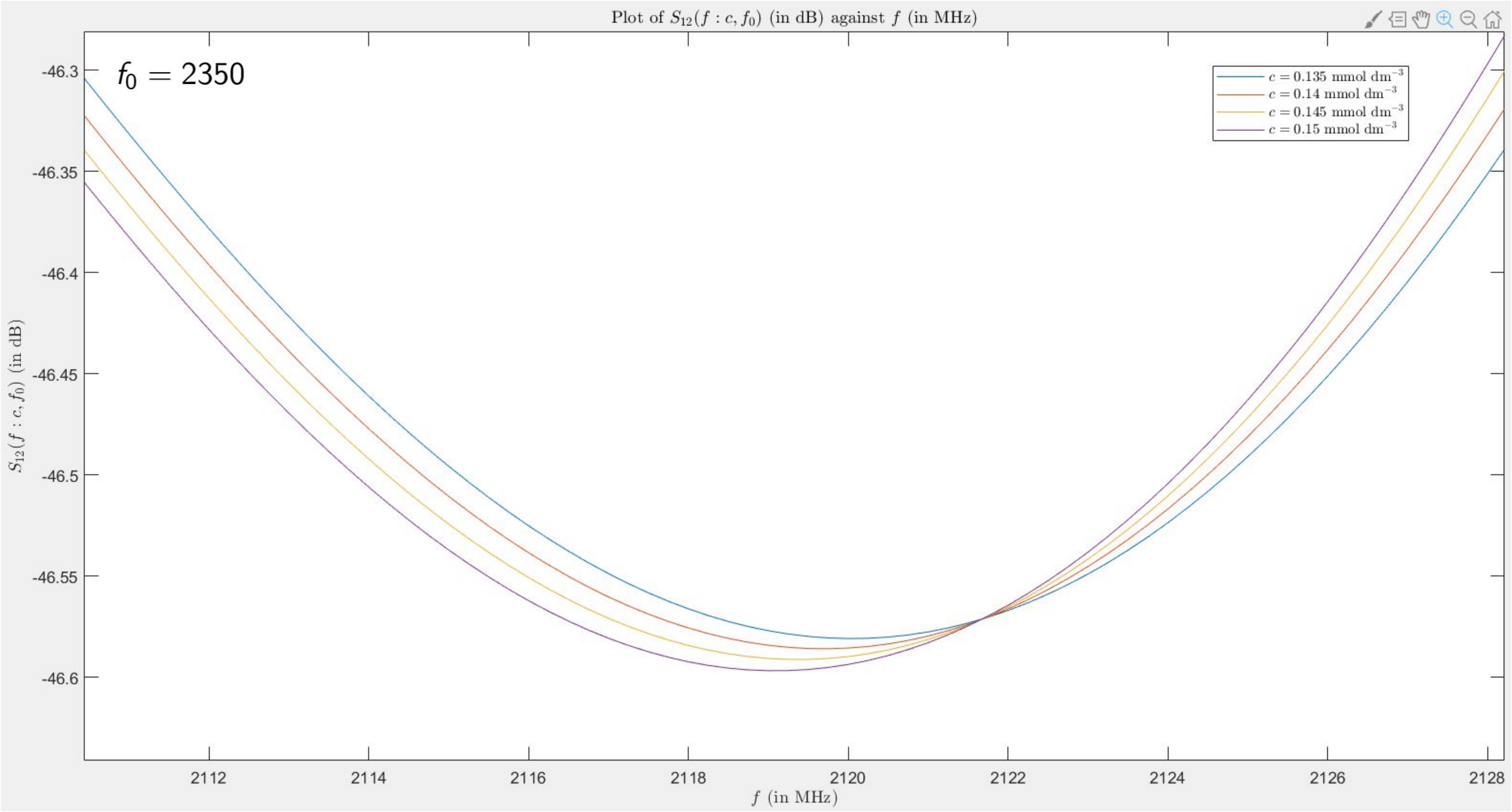
- 'S' is replaced as S_{11}, S_{12}, S_{21}, S_{22} when specifying the respective S-parameter considered
- c denotes the concentration of NaCl (in mmol dm^{-3})
- f_0 denotes the resonant frequency (in MHz) the setup is designed for
- f denotes the frequency (in MHz) corresponding to the value of the S parameter



Plot of $S_{12}(f : c, f_0)$ (in dB) against f (in MHz)
$f_0 = 2350$
$c = 0.135$ mmol dm^{-3}
$c = 0.14$ mmol dm^{-3}
$c = 0.145$ mmol dm^{-3}
$c = 0.15$ mmol dm^{-3}
$S_{12}(f : c, f_0)$ (in dB)
f (in MHz)
-15
-20
-25
-30
-35
-40
-45
-50
2100
2150
2200
2250
2300
2350
2400



Plot of $S_{12}(f : c, f_0)$ (in dB) against f (in MHz)
$f_0 = 2350$
$c = 0.135$ mmol dm^{-3}
$c = 0.14$ mmol dm^{-3}
$c = 0.145$ mmol dm^{-3}
$c = 0.15$ mmol dm^{-3}
$S_{12}(f : c, f_0)$ (in dB)
-33.4
-33.5
-33.6
-33.7
-33.8
-33.9
2257.5
2258
2258.5
2259
2259.5
2260
2260.5
2261
2261.5
2262
2262.5
f (in MHz)


Plot of $S_{12}(f : c, f_0)$ (in dB) against f (in MHz)
$f_0 = 2350$
$c = 0.135$ mmol dm^{-3}
$c = 0.14$ mmol dm^{-3}
$c = 0.145$ mmol dm^{-3}
$c = 0.15$ mmol dm^{-3}
$S_{12}(f : c, f_0)$ (in dB)
f (in MHz)
-46.3
-46.35
-46.4
-46.45
-46.5
-46.55
-46.6
2112
2114
2116
2118
2120
2122
2124
2126
2128

Statistical techniques

The unbiased estimate for population mean, denoted by $\hat{\mu}$ is defined by

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

The unbiased estimate for population variance, denoted by $\hat{\sigma}^2$ is defined as

$$\hat{\sigma}^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \hat{\mu})^2$$

According to the 68-95-99.7 rule,

$$\begin{aligned} P(\mu - \sigma \leq X \leq \mu + \sigma) &= \quad 0.6827 \\ P(\mu - 2\sigma \leq X \leq \mu + 2\sigma) &= \quad 0.9545 \\ P(\mu - 3\sigma \leq X \leq \mu + 3\sigma) &= \quad 0.9973 \end{aligned}$$

Execution

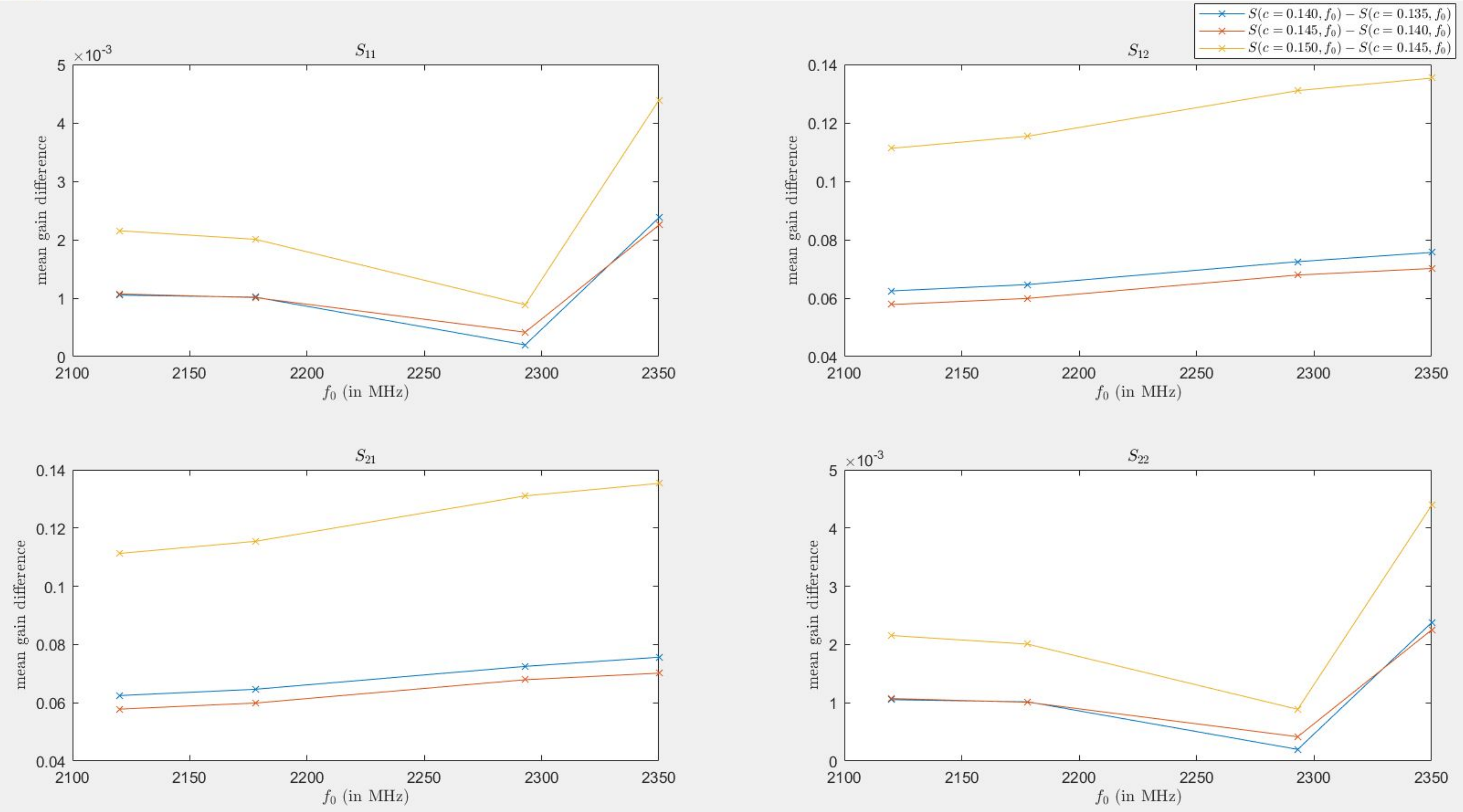
We found that the differences between some S-parameters are greater than others, but this comes at a cost of greater variance (less consistent and more prone to sign changes). We consider the following vector

$$\begin{bmatrix} S(f : c_2, f_0) - S(f : c_1, f_0) \\ S(f : c_3, f_0) - S(f : c_2, f_0) \\ S(f : c_4, f_0) - S(f : c_3, f_0) \end{bmatrix}$$

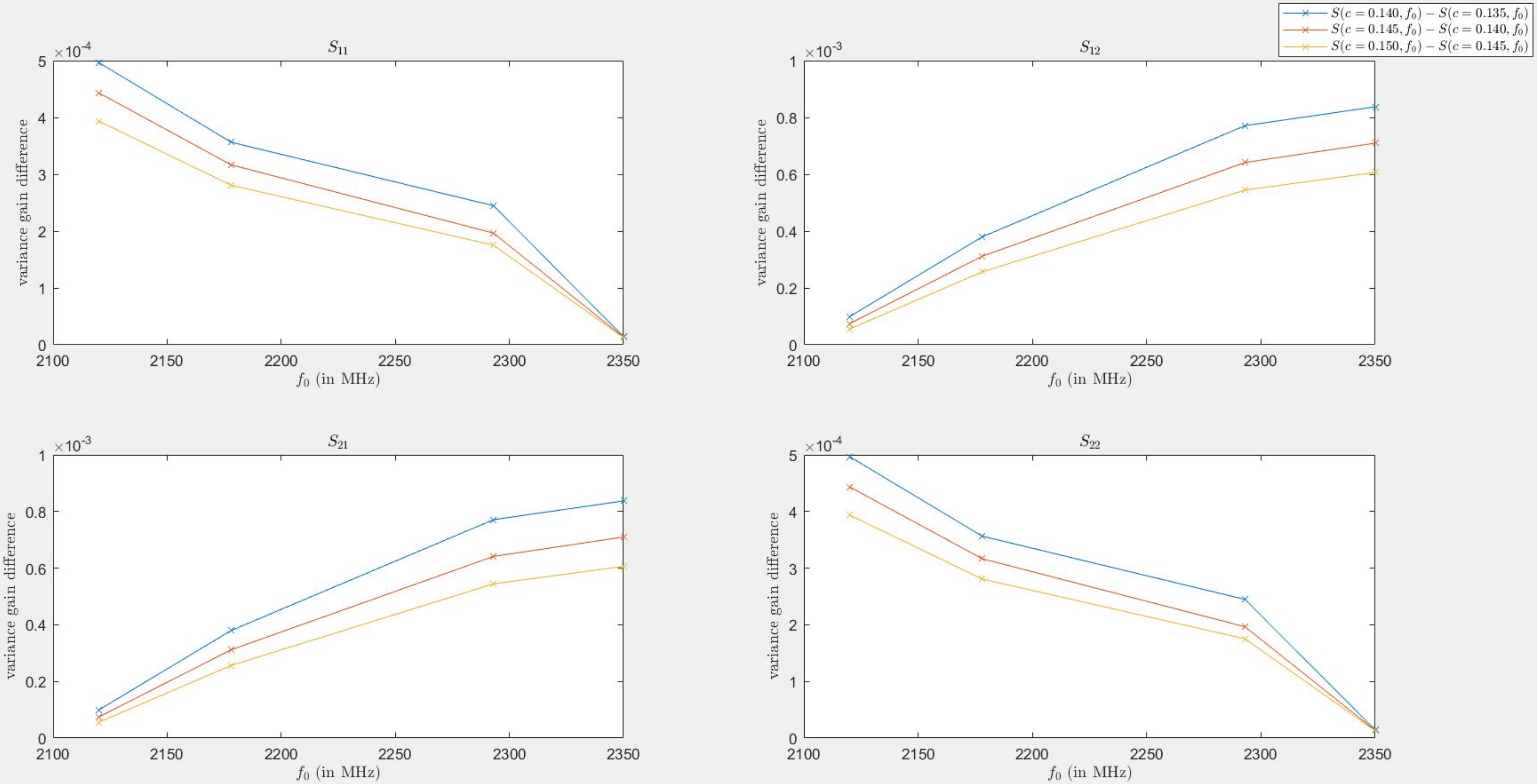
for all S (S_{11}, S_{12}, S_{21} and S_{22}) and subject to $c_1 < c_2 < c_3 < c_4$

Find the optimal S-parameter and f_0 that

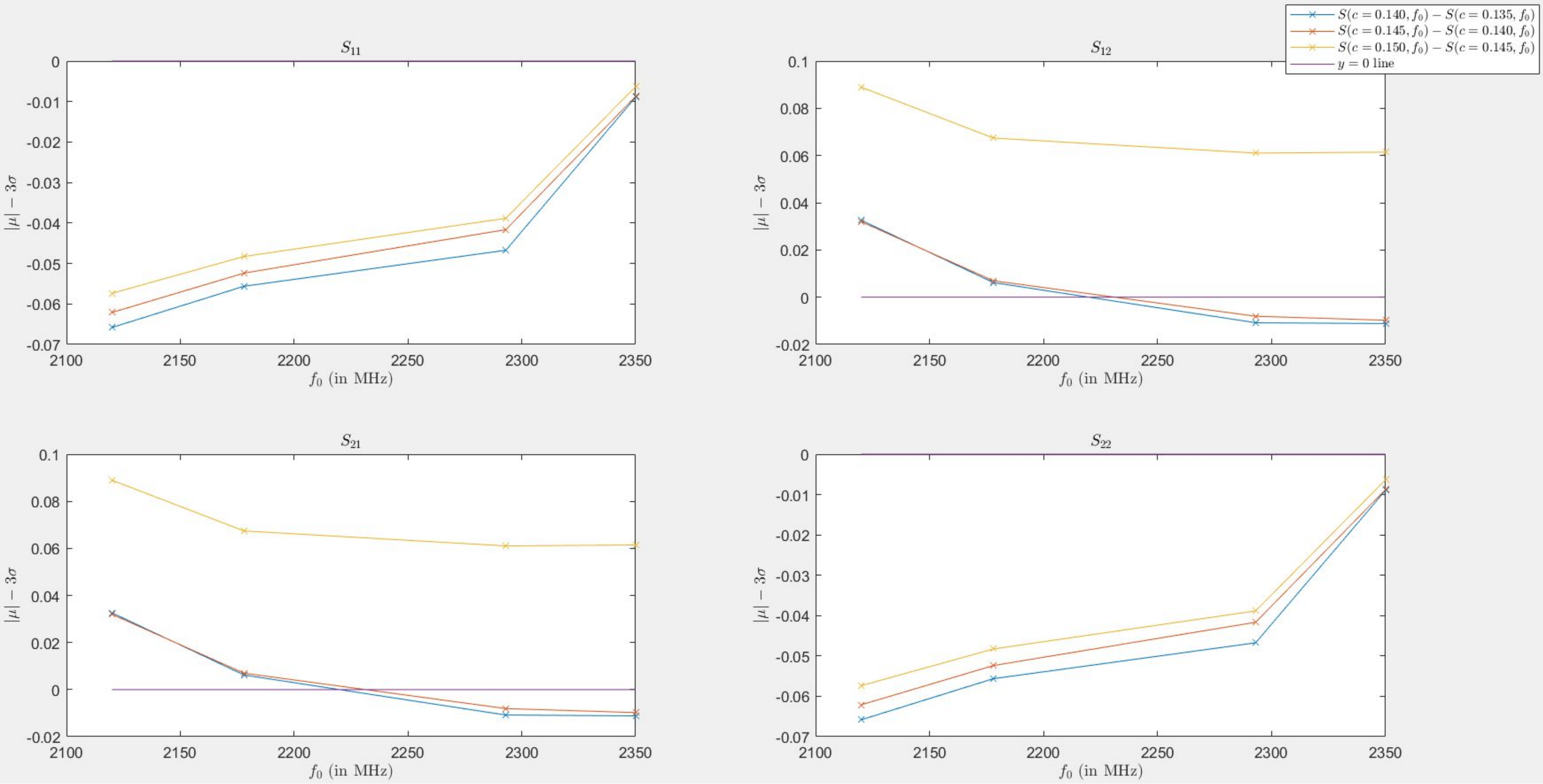
- has the greatest absolute mean for all components
- has the variance s.t. $|\hat{\mu}| - 3\hat{\sigma} \geq 0$ (strict condition)
- the sign ($+$ or $-$) of each component in the mean matrix must be consistent



$S(c=0.140, f_0) - S(c=0.135, f_0)$
$S(c=0.145, f_0) - S(c=0.140, f_0)$
$S(c=0.150, f_0) - S(c=0.145, f_0)$
S_{11}
S_{12}
S_{21}
S_{22}
mean gain difference
f_0 (in MHz)
$\times 10^{-3}$

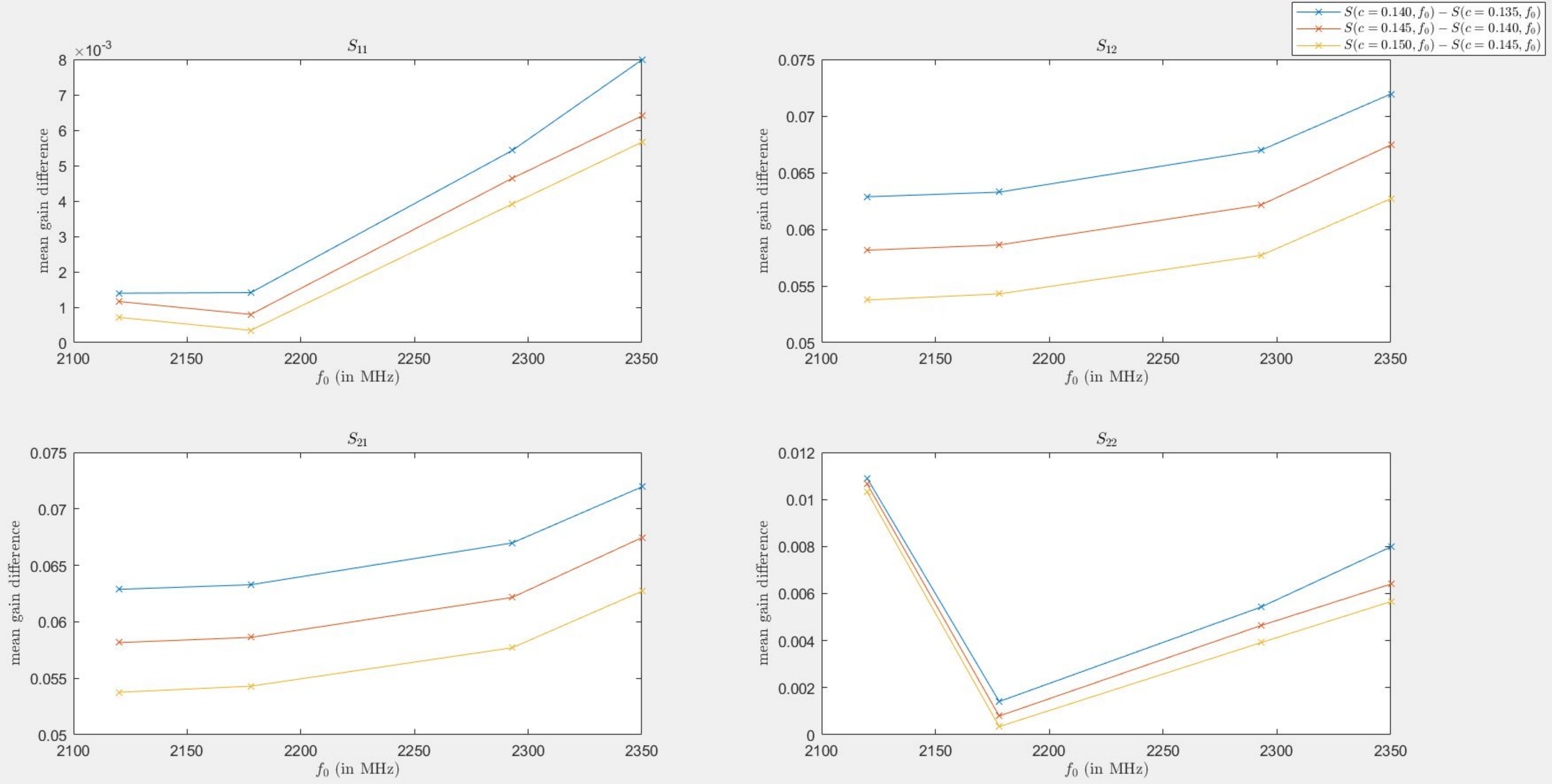


$S(c=0.140, f_0) - S(c=0.135, f_0)$
$S(c=0.145, f_0) - S(c=0.140, f_0)$
$S(c=0.150, f_0) - S(c=0.145, f_0)$
S_{11}
S_{12}
S_{21}
S_{22}
variance gain difference
f_0 (in MHz)
$\times 10^{-4}$
$\times 10^{-3}$

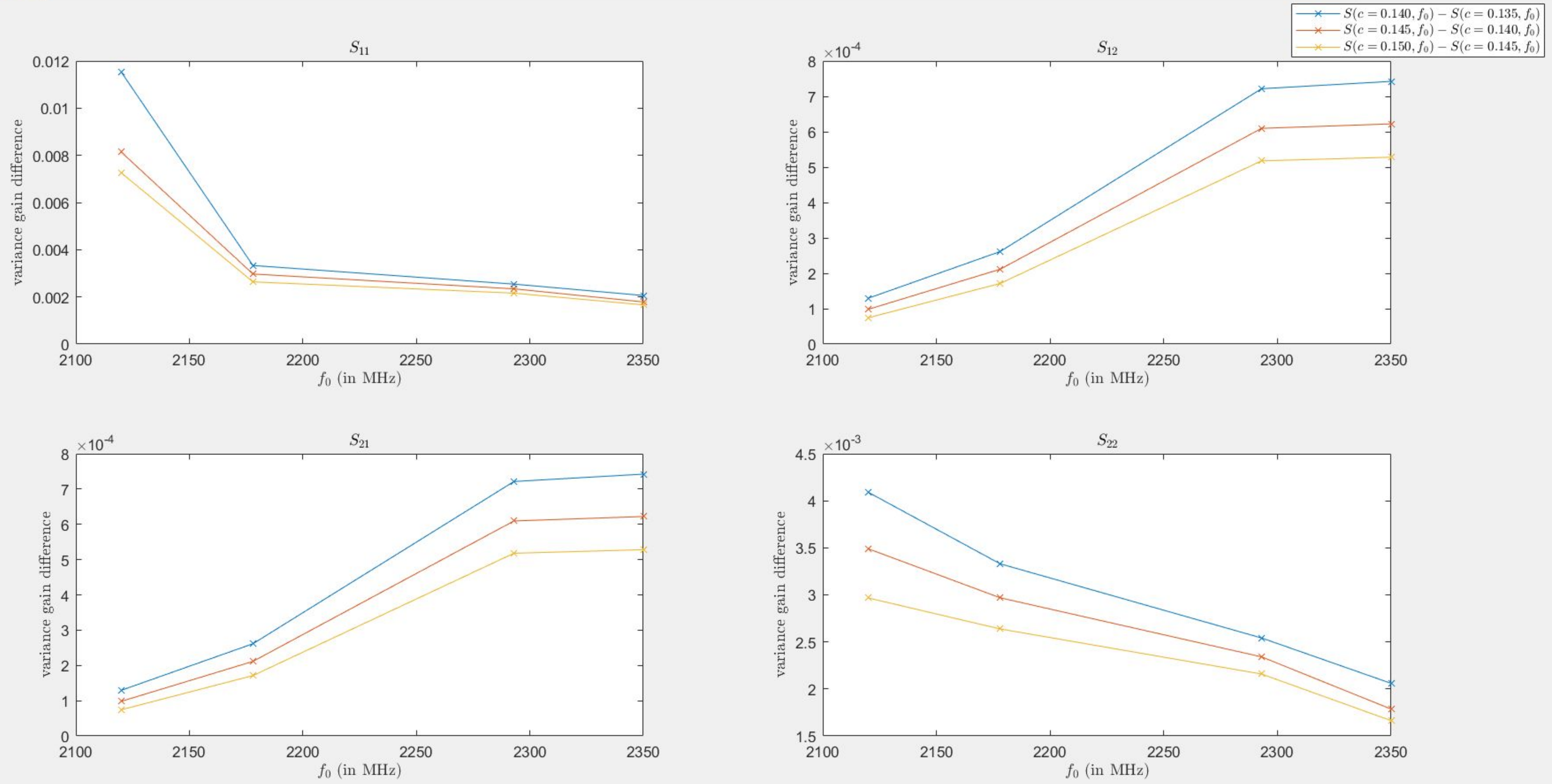


$S(c = 0.140, f_0) - S(c = 0.135, f_0)$
$S(c = 0.145, f_0) - S(c = 0.140, f_0)$
$S(c = 0.150, f_0) - S(c = 0.145, f_0)$
$y = 0$ line
S_{11}
S_{12}
S_{21}
S_{22}
$|\mu| - 3\sigma$
f_0 (in MHz)

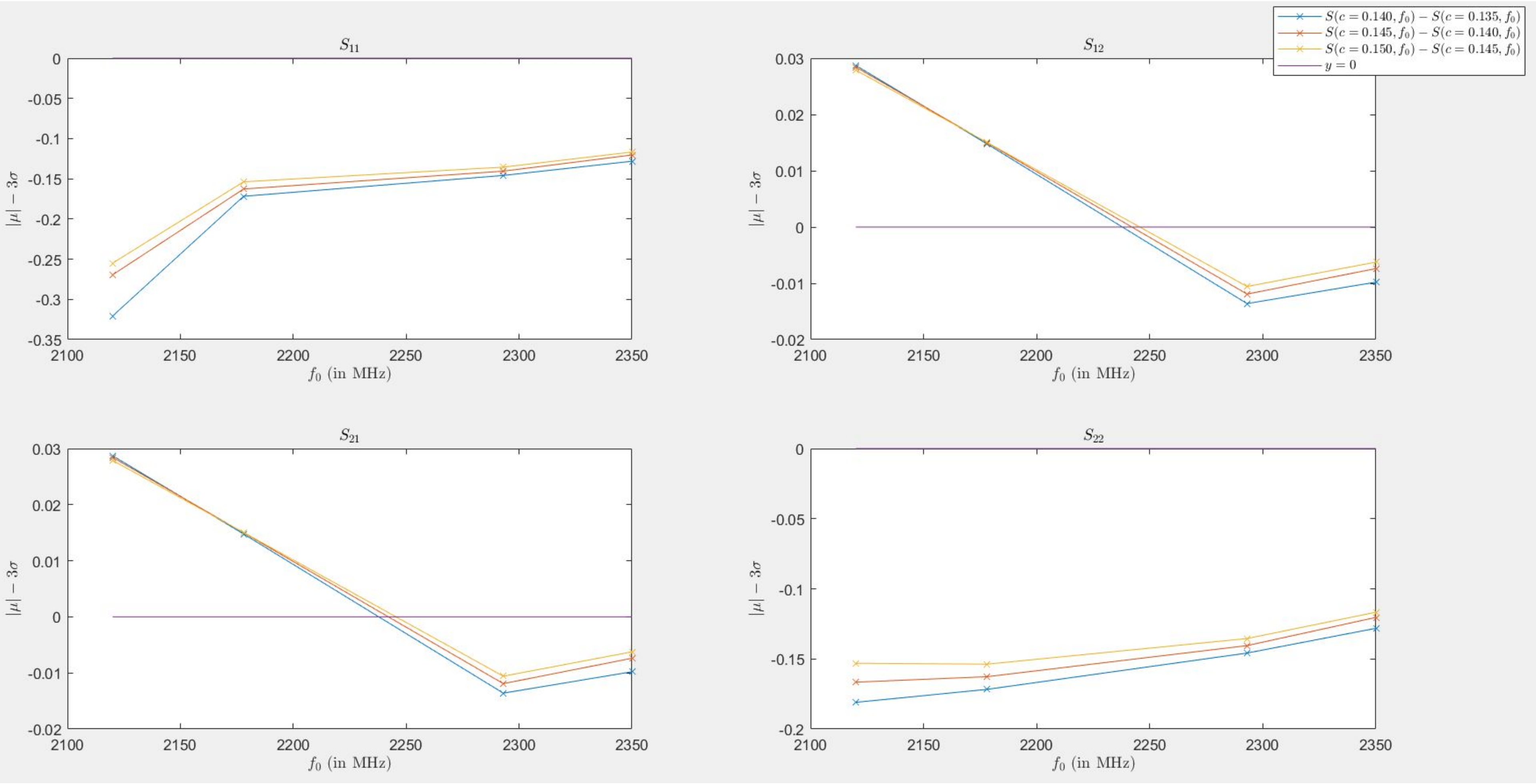
What if we do matching?



$S(c=0.140, f_0) - S(c=0.135, f_0)$
$S(c=0.145, f_0) - S(c=0.140, f_0)$
$S(c=0.150, f_0) - S(c=0.145, f_0)$
S_{11}
$\times 10^{-3}$
8
7
6
5
4
3
2
1
0
mean gain difference
2100
2150
2200
2250
2300
2350
f_0 (in MHz)
S_{12}
0.075
0.07
0.065
0.06
0.055
0.05
mean gain difference
2100
2150
2200
2250
2300
2350
f_0 (in MHz)
S_{21}
0.075
0.07
0.065
0.06
0.055
0.05
mean gain difference
2100
2150
2200
2250
2300
2350
f_0 (in MHz)
S_{22}
0.012
0.01
0.008
0.006
0.004
0.002
0
mean gain difference
2100
2150
2200
2250
2300
2350
f_0 (in MHz)

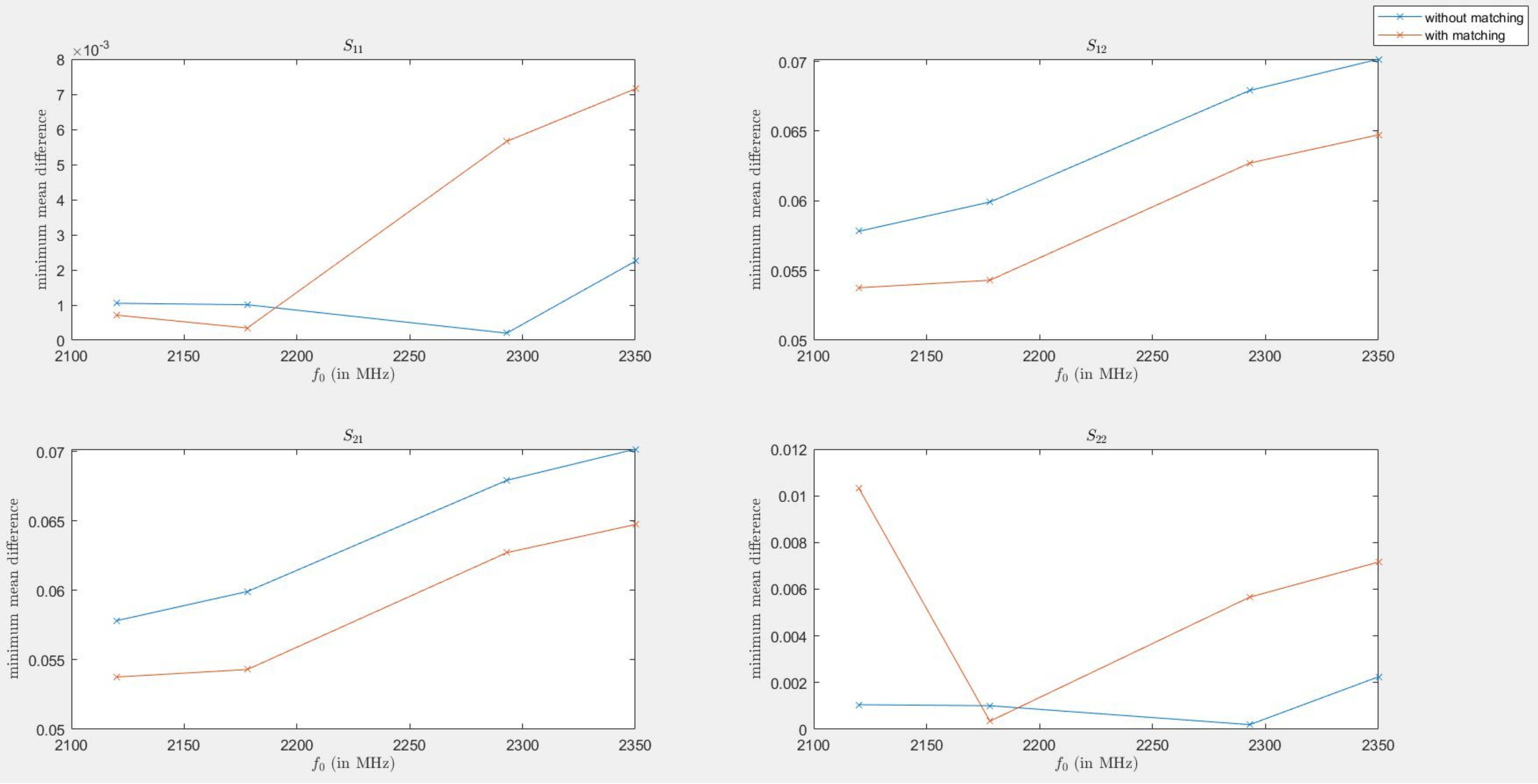


$S(c=0.140, f_0) - S(c=0.135, f_0)$
$S(c=0.145, f_0) - S(c=0.140, f_0)$
$S(c=0.150, f_0) - S(c=0.145, f_0)$
S_{11}
S_{12}
S_{21}
S_{22}
variance gain difference
f_0 (in MHz)
$\times 10^{-4}$
$\times 10^{-3}$

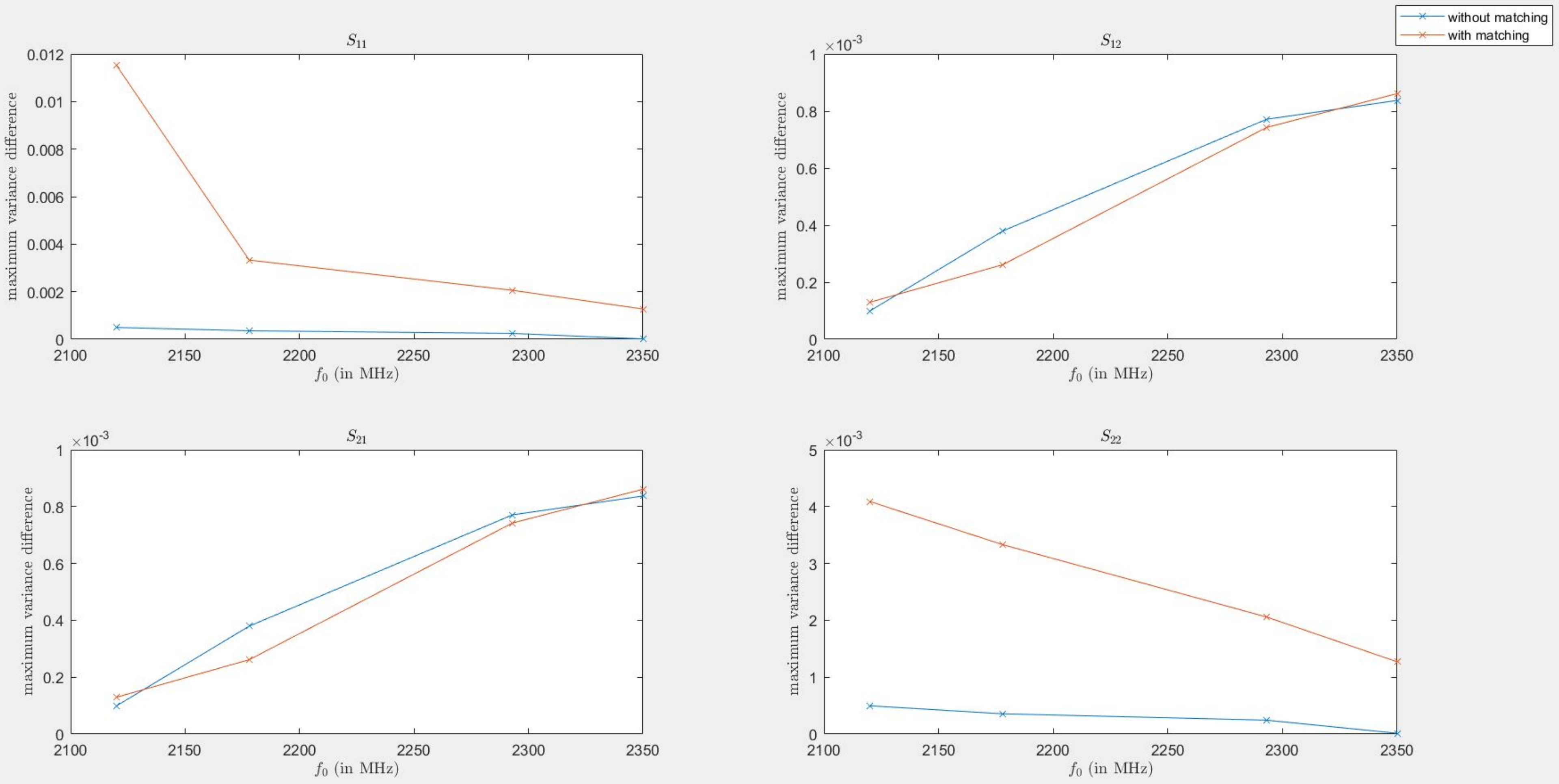


$S(c=0.140, f_0) - S(c=0.135, f_0)$
$S(c=0.145, f_0) - S(c=0.140, f_0)$
$S(c=0.150, f_0) - S(c=0.145, f_0)$
$y = 0$
S_{11}
S_{12}
S_{21}
S_{22}
$|\mu| - 3\sigma$
f_0 (in MHz)
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
0.03
0.02
0.01
-0.01
-0.02
2100
2150
2200
2250
2300
2350

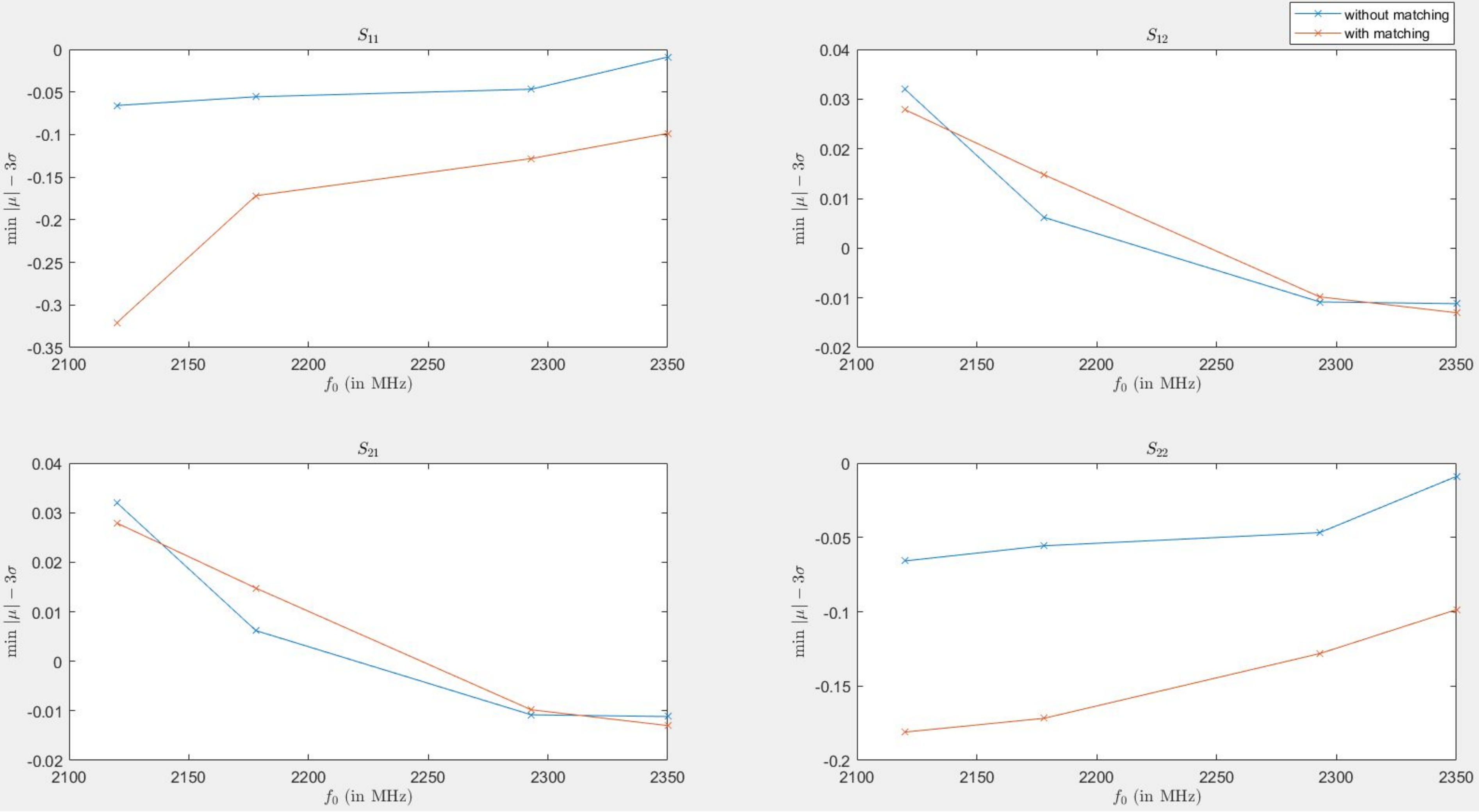
Matching vs no matching



without matching
with matching
S_{11}
$\times 10^{-3}$
S_{12}
S_{21}
S_{22}
minimum mean difference
f_0 (in MHz)

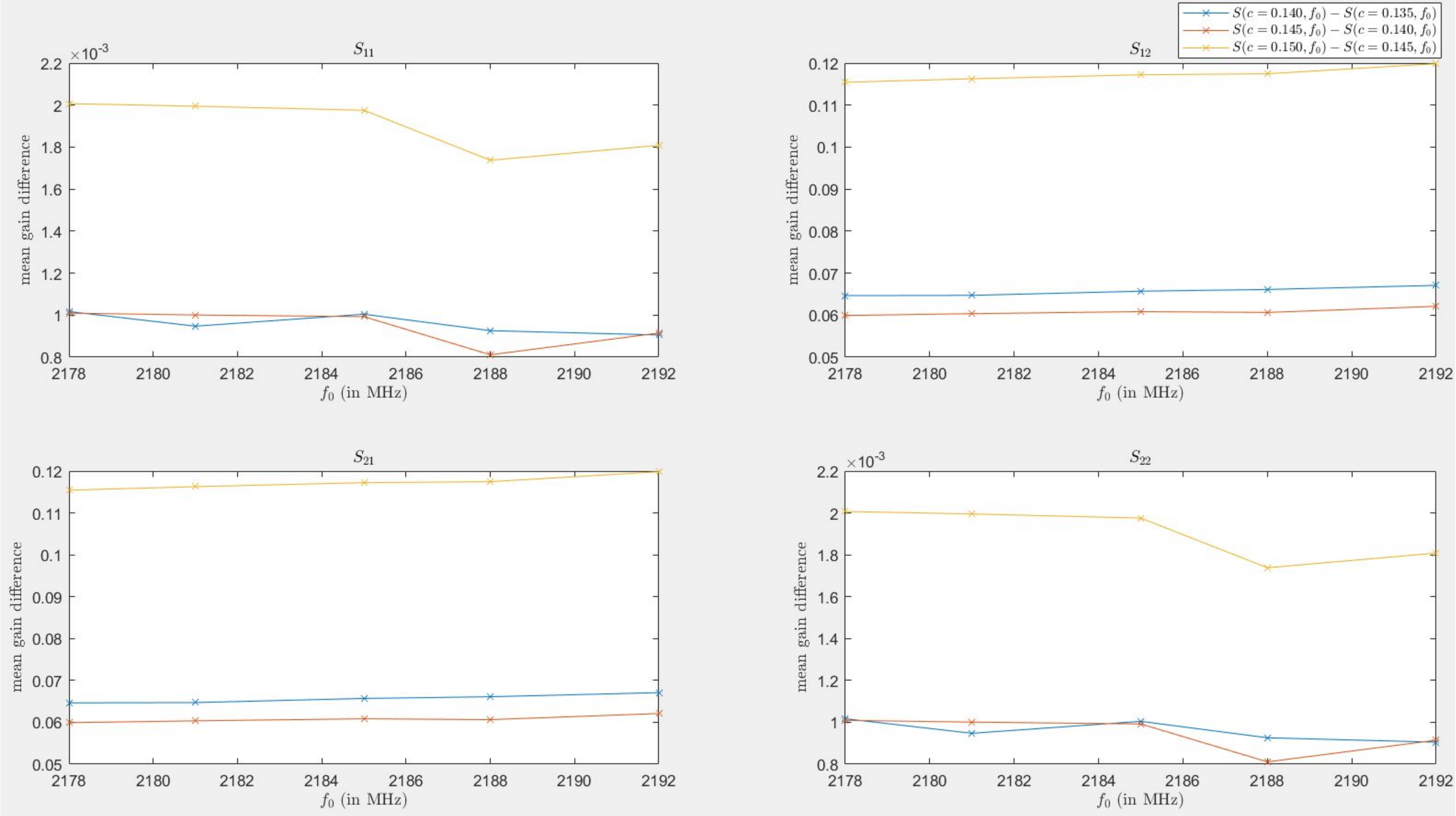


without matching
with matching
S_{11}
S_{12}
S_{21}
S_{22}
maximum variance difference
f_0 (in MHz)
$\times 10^{-3}$
0.012
0.01
0.008
0.006
0.004
0.002
0
1
0.8
0.6
0.4
0.2
5
4
3
2
2100
2150
2200
2250
2300
2350

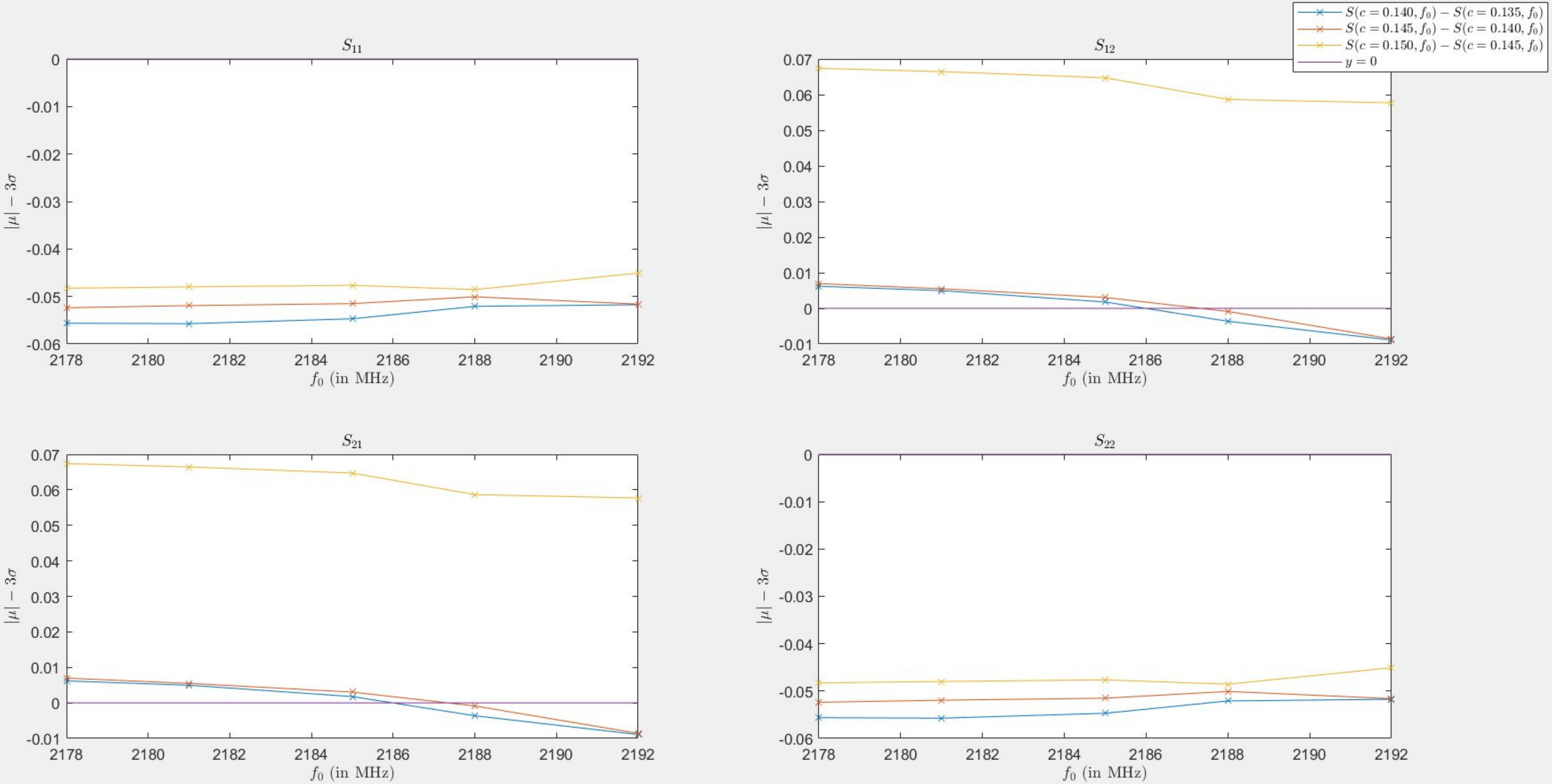


without matching
with matching
S_{11}
S_{12}
S_{21}
S_{22}
$\min|\mu| - 3\sigma$
f_0 (in MHz)

Going deeper...



$S(c=0.140, f_0) - S(c=0.135, f_0)$
$S(c=0.145, f_0) - S(c=0.140, f_0)$
$S(c=0.150, f_0) - S(c=0.145, f_0)$
S_{11}
S_{12}
S_{21}
S_{22}
$\times 10^{-3}$
mean gain difference
f_0 (in MHz)



$S(c = 0.140, f_0) - S(c = 0.135, f_0)$
$S(c = 0.145, f_0) - S(c = 0.140, f_0)$
$S(c = 0.150, f_0) - S(c = 0.145, f_0)$
$y = 0$
S_{11}
S_{12}
S_{21}
S_{22}
$|\mu| - 3\sigma$
f_0 (in MHz)
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
0.07
0.06
0.05
0.04
0.03
0.02
0.01
2178
2180
2182
2184
2186
2188
2190
2192

From Eq 7.109 in Chapter 7 of the textbook,

$$\vec{S}_{av}(z) = \hat{z}\frac{\left|\widetilde{E}(0)\right|^2}{2|\eta_c|}e^{-2\alpha z}\cos(\theta_\eta)$$

The complex intrinsic impedance is given by

$$\eta_c = \sqrt{\frac{\mu}{\varepsilon'}}\left(1 - j\frac{\varepsilon''}{\varepsilon'}\right)^{-\frac{1}{2}}$$

With the real and imaginary parts of permittivity being $\varepsilon' = \varepsilon$ and $\varepsilon'' = \frac{\sigma}{\omega}$, we get

$$\eta_c = \sqrt{\frac{\mu}{\varepsilon}}\left(1 - j\frac{\sigma}{\omega\varepsilon}\right)^{-\frac{1}{2}}$$

The attenuation constant α is given by

$$\alpha = \omega\left\{\frac{\mu\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right]\right\}^{\frac{1}{2}}$$

Substituting the expressions for ε' and ε'' we get

$$\alpha = \omega\left\{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right]\right\}^{\frac{1}{2}}$$

With $\varepsilon = \varepsilon_r\varepsilon_0$ and $\mu = \mu_r\mu_0$,

$$\eta_c = \sqrt{\frac{\mu_r\mu_0}{\varepsilon_r\varepsilon_0}}\left(1 - j\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)^{-\frac{1}{2}}$$

$$\alpha = \omega\left\{\frac{\mu_r\mu_0\varepsilon_r\varepsilon_0}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)^2} - 1\right]\right\}^{\frac{1}{2}}$$

Expressing η_c in polar form, we have

$$\eta_c = \sqrt{\frac{\mu_r\mu_0}{\varepsilon_r\varepsilon_0}}\left(\sqrt{1+\frac{\sigma^2}{\omega^2{\varepsilon_r}^2{\varepsilon_0}^2}}\exp\left[j\arctan\left(-\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)\right]\right)^{-\frac{1}{2}}$$

$$= \sqrt{\frac{\mu_r\mu_0}{\varepsilon_r\varepsilon_0}}\left(1+\frac{\sigma^2}{\omega^2{\varepsilon_r}^2{\varepsilon_0}^2}\right)^{-\frac{1}{4}}\exp\left[j\frac{1}{2}\arctan\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)\right]$$

The expression for the ratio $\frac{\vec{S}_{av}(z)}{\left|\widetilde{E}(0)\right|^2}$ becomes

$$\hat{z}\frac{1}{2\sqrt{\frac{\mu_r\mu_0}{\varepsilon_r\varepsilon_0}}\left(1+\frac{\sigma^2}{\omega^2{\varepsilon_r}^2{\varepsilon_0}^2}\right)^{-\frac{1}{4}}}\exp\left\{-2\omega z\left\{\frac{\mu_r\mu_0\varepsilon_r\varepsilon_0}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)^2}-1\right]\right\}^{\frac{1}{2}}\right\}$$

$$\cos\left[\frac{1}{2}\arctan\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)\right]$$

$$S_{av} = \hat{z}\left(\frac{1}{\sqrt{\frac{\mu}{\varepsilon_r \varepsilon_o}}\sqrt{1^2 + \frac{\sigma^2}{\omega^2 \varepsilon_r \varepsilon_o}}} e^{-\omega\sqrt{\frac{\mu\varepsilon_r\varepsilon_o}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_o}\right)^2}-1\right)}}\right) \times cos\frac{1}{2}\, tan^{-1}\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_o}\right)$$

$$\mu = 0.999991 \times 10^7 \times 4\pi \ \mathrm{H/m}$$

$$\varepsilon_r = 78.3 - [\mathrm{NaCl}]\ 11.7$$

$$\varepsilon_o = \frac{1}{36\times 10^9}\mathrm{F/m}$$

$$\omega = 2350 \ \mathrm{rad}s^{-1}$$

$$-\frac{e^{-\frac{1}{2}em(-ac+r)\sqrt{-1+\sqrt{1+e(-ac+r)(bc+si)^2}}\,v}\left(2be^2(-ac+r)^2(bc+si)-2ae^2(-ac+r)(bc+si)^2\right)\mathrm{Cos}\left[0.5\,\mathrm{ArcTan}\left[\frac{bc+si}{e(-ac+r)v}\right]\right]}{4\sqrt{\frac{m}{e(-ac+r)}}\left(1+e^2(-ac+r)^2(bc+si)^2\right)^{5/4}}-\frac{a\,e^{-\frac{1}{2}em(-ac+r)\sqrt{-1+\sqrt{1+e(-ac+r)(bc+si)^2}}\,v}\,m\,\mathrm{Cos}\left[0.5\,\mathrm{ArcTan}\left[\frac{bc+si}{e(-ac+r)v}\right]\right]}{2e\left(\frac{m}{e(-ac+r)}\right)^{3/2}(-ac+r)^2\left(1+e^2(-ac+r)^2(bc+si)^2\right)^{1/4}}$$

$$+\frac{e^{-\frac{1}{2}em(-ac+r)\sqrt{-1+\sqrt{1+e(-ac+r)(bc+si)^2}}\,v}\left(-\frac{em(-ac+r)\left(2be(-ac+r)(bc+si)-ae(bc+si)^2\right)v}{8\sqrt{1+e(-ac+r)(bc+si)^2}\sqrt{-1+\sqrt{1+e(-ac+r)(bc+si)^2}}}+\frac{1}{2}aem\sqrt{-1+\sqrt{1+e(-ac+r)(bc+si)^2}}\,v\right)\mathrm{Cos}\left[0.5\,\mathrm{ArcTan}\left[\frac{bc+si}{e(-ac+r)v}\right]\right]}{\sqrt{\frac{m}{e(-ac+r)}}\left(1+e^2(-ac+r)^2(bc+si)^2\right)^{1/4}}$$

$$-\frac{0.5\,e^{-\frac{1}{2}em(-ac+r)\sqrt{-1+\sqrt{1+e(-ac+r)(bc+si)^2}}\,v}\left(\frac{b}{e(-ac+r)v}+\frac{a(bc+si)}{e(-ac+r)^2v}\right)\mathrm{Sin}\left[0.5\,\mathrm{ArcTan}\left[\frac{bc+si}{e(-ac+r)v}\right]\right]}{\sqrt{\frac{m}{e(-ac+r)}}\left(1+e^2(-ac+r)^2(bc+si)^2\right)^{1/4}\left(1+\frac{(bc+si)^2}{e^2(-ac+r)^2v^2}\right)}$$

- mu=m

  Er = r-a*c

  Enot = e

  w=w

  sigma =si+b*c