Design a rectangular microstrip antenna to operate at a frequency of 1.5 GHz on a Rogers Corporation RO4003C substrate- assume h = 0.813 mm = 0.032", 1 oz. copper cladding (34 μm), loss tangent tan(δ) = 0.0022, and a relative dielectric constant ε_r = 3.38. The antenna is to be matched to a 50 Ω microstrip transmission line on this substrate. Discuss and justify design choices. Accurately sketch a top view of the final design.

EE 583 only- Include a fully-labeled Smith chart showing the normalized admittances $y_1 = y_2$ & y_{2t} (i.e., y_2 translated across length $L + \Delta L$ of microstrip antenna) and discuss results.

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<u>Design Procedure (All calculations done using to full precision of/on MathCad)</u>

1) Specify ε_r and h of substrate, the desired resonant frequency f_r, and the impedance $Z_{c,\text{feed}}$ of the feeding transmission line.

$$\boldsymbol{\varepsilon_r = 3.38, \quad h = 0.813\text{ mm} = 0.032\text{ in}, \quad f_r = 1.5\text{ GHz}, \quad \&\ Z_{c,\text{feed}} = 50\,\Omega}$$

2) Calculate width of patch using (14-6)

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{2.9979\times10^8}{2(1.5\times10^9)}\sqrt{\frac{2}{3.38+1}} \Rightarrow \underline{\mathbf{W = 67.527\text{ mm}}}$$

3) Calculate effective relative permittivity using (14-1)

$$\varepsilon_{\text{r,eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-0.5} = \frac{3.38+1}{2} + \frac{3.38-1}{2}\left[1 + 12\frac{0.813}{67.527}\right]^{-0.5} \Rightarrow \underline{\boldsymbol{\varepsilon_{\text{r,eff}} = 3.30236}}$$

4) Calculate fringing length using (14-2)

$$\Delta L = 0.412h\frac{(\varepsilon_{\text{r,eff}} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{\text{r,eff}} - 0.258)\left(\frac{W}{h} + 0.8\right)} = 0.412(0.813)\frac{(3.3024 + 0.3)\left(\frac{67.527}{0.813} + 0.264\right)}{(3.3024 - 0.258)\left(\frac{67.527}{0.813} + 0.8\right)}$$

$$\Rightarrow \underline{\boldsymbol{\Delta L = 0.3938\text{ mm}}}$$

5) Calculate the effective length (14-5) and guided wavelength λ.

$$L_{\text{eff}} = \frac{c}{2f_r\sqrt{\varepsilon_{\text{r,eff}}}} = \frac{2.9979\times10^8}{2(1.5\times10^9)\sqrt{3.30236}} \Rightarrow \underline{\boldsymbol{L_{\text{eff}} = 54.99\text{ mm}}}$$

and

$$\lambda = 2L_{\text{eff}} = 2(54.99) \Rightarrow \underline{\boldsymbol{\lambda = 109.98\text{ mm}}}$$

6) Calculate the patch length L (14-7) and L/λ. Then, calculate and check that $W/L < 2$.

$L = L_{eff} - 2\Delta L = 54.99 - 2(0.3938) \quad \Rightarrow \quad \underline{\mathbf{L = 54.203\ mm}}$

$L/\lambda = 54.203/109.98 \quad \Rightarrow \quad \underline{\mathbf{L/\lambda = 0.4928}}$

$W/L = 67.527/54.203 \quad \Rightarrow \quad \underline{\mathbf{W/L = 1.246}}$ **(should be OK as it's < 2)**

7) Calculate $G_1 \approx G_2$ and $B_1 \approx B_2$.

$$G_{1,est} = \frac{W}{120\lambda_0}\left[1 - \frac{1}{24}(k_0 h)^2\right] \quad \text{for } \frac{h}{\lambda_0} < \frac{1}{10} \quad (14-8a)$$

$$B_{1,est} = \frac{W}{120\lambda_0}\left[1 - 0.636\ln(k_0 h)\right] \quad \text{for } \frac{h}{\lambda_0} < \frac{1}{10} \quad (14-8b)$$

where

$\lambda_0 = c/f_r = 2.9979\times10^8 / 1.5\times10^9 \quad \Rightarrow \quad \lambda_0 = 199.862$ mm,

$h/\lambda_0 = 0.813/199.862 \quad \Rightarrow \quad h/\lambda_0 = 0.004068$,

and $k_0 = 2\pi/\lambda_0 = 2\pi/0.199862 \quad \Rightarrow \quad k_0 = 31.4377$ rad/m,

$$G_{1,est} = \frac{67.527}{120(199.862)}\left[1 - \frac{1}{24}\left(34.4377 * 0.813 * 10^{-3}\right)^2\right] \quad \Rightarrow \quad \underline{G_{1,est} = 2.8155\ \text{mS}}$$

$$B_{1,est} = \frac{67.527}{120(199.862)}\left[1 - 0.636\ln\left(34.4377 * 0.813 * 10^{-3}\right)\right] \quad \Rightarrow \quad \underline{B_{1,est} = 9.3817\ \text{mS}}$$

numerically integrate (notes & 14-12a)-

$$G_1 = \frac{1}{\pi\eta_0}\int_{\theta=0}^{\pi}\left[\frac{\sin\left(\frac{k_0 W}{2}\cos\theta\right)}{\cos\theta}\right]^2 \sin^3\theta\, d\theta$$

$$= \frac{1}{\pi(376.73)}\int_{\theta=0}^{\pi}\left[\frac{\sin\left(\frac{34.438(0.06753)}{2}\cos\theta\right)}{\cos\theta}\right]^2 \sin^3\theta\, d\theta \quad \Rightarrow \quad \underline{\mathbf{G_1 = 1.1798\ mS}}$$

(notes) $B_1 = \left(\dfrac{G_1}{G_{1,est}}\right)B_{1,est} = \left(\dfrac{1.1798}{2.8155}\right)9.3817 \quad \Rightarrow \quad \underline{\mathbf{B_1 = 3.9313\ mS}}$.

Therefore, $Y_1 = Y_2 = G_1 + j\,B_1 \quad \Rightarrow \quad \underline{\mathbf{Y_1 = Y_2 = 1.1798 + j\,3.9313\ mS}}$

8) Calculate the TL characteristic impedance $Z_{c,\text{ant}}$ (14-19a) and admittance $Y_{c,\text{ant}}$ for the rectangular microstrip antenna.

$$Z_{c,\text{ant}} = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_{\text{r,eff}}}} \ln\left[\dfrac{8h}{W} + \dfrac{W}{4h}\right] & \dfrac{W}{h} \le 1 \\ \dfrac{\eta_0}{\sqrt{\varepsilon_{\text{r,eff}}}\left[\dfrac{W}{h} + 1.393 + 0.667\ln\left(\dfrac{W}{h} + 1.444\right)\right]} & \dfrac{W}{h} > 1 \end{cases}$$

here $W/h = 67.527/0.813 = 83.059$ and

$$Z_{c,\text{ant}} = \frac{376.73}{\sqrt{3.30236}\left[83.059 + 1.393 + 0.667\ln\left(83.059 + 1.444\right)\right]} \quad \Rightarrow \quad \underline{\mathbf{Z_{c,ant} = 2.3717\ \Omega}}$$

and

$$Y_{c,\text{ant}} = \frac{1}{Z_{c,\text{ant}}} = \frac{1}{2.3717} \quad \Rightarrow \quad \underline{\mathbf{Y_{c,ant} = 0.4216\ S}}$$

9) (**EE 583**) Use Smith chart or direct calculation to verify $\tilde{Y}_2 = \tilde{G}_2 + j\tilde{B}_2 \approx G_1 - jB_1 = Y_1^*$.

On Smith chart (next page), plot $y_2 = Y_2/Y_{c,\text{ant}} = (1.1798 + j\,3.9313)10^{-3}\,(2.3717)$

$\Rightarrow$ $\underline{y_2 = 0.0028 + j0.0093 \text{ S/S}}$.

Move $(L+\Delta L)/\lambda = (54.203+0.3938)/109.98 = 0.4964$ WAVELENGTHS TOWARD GENERATOR on arc of constant $|\Gamma|$.

On Smith chart, read off $\Rightarrow$ $\underline{y_{2t} = 0.0028 - j\,0.013 \text{ S/S}}$.

We approximately meet the condition that-

$\underline{y_{2t} = 0.0028 - j0.013 \text{ S/S} \approx y_1^* = 0.0028 - j0.0093 \text{ S/S}}$ (~15% error on susceptance)

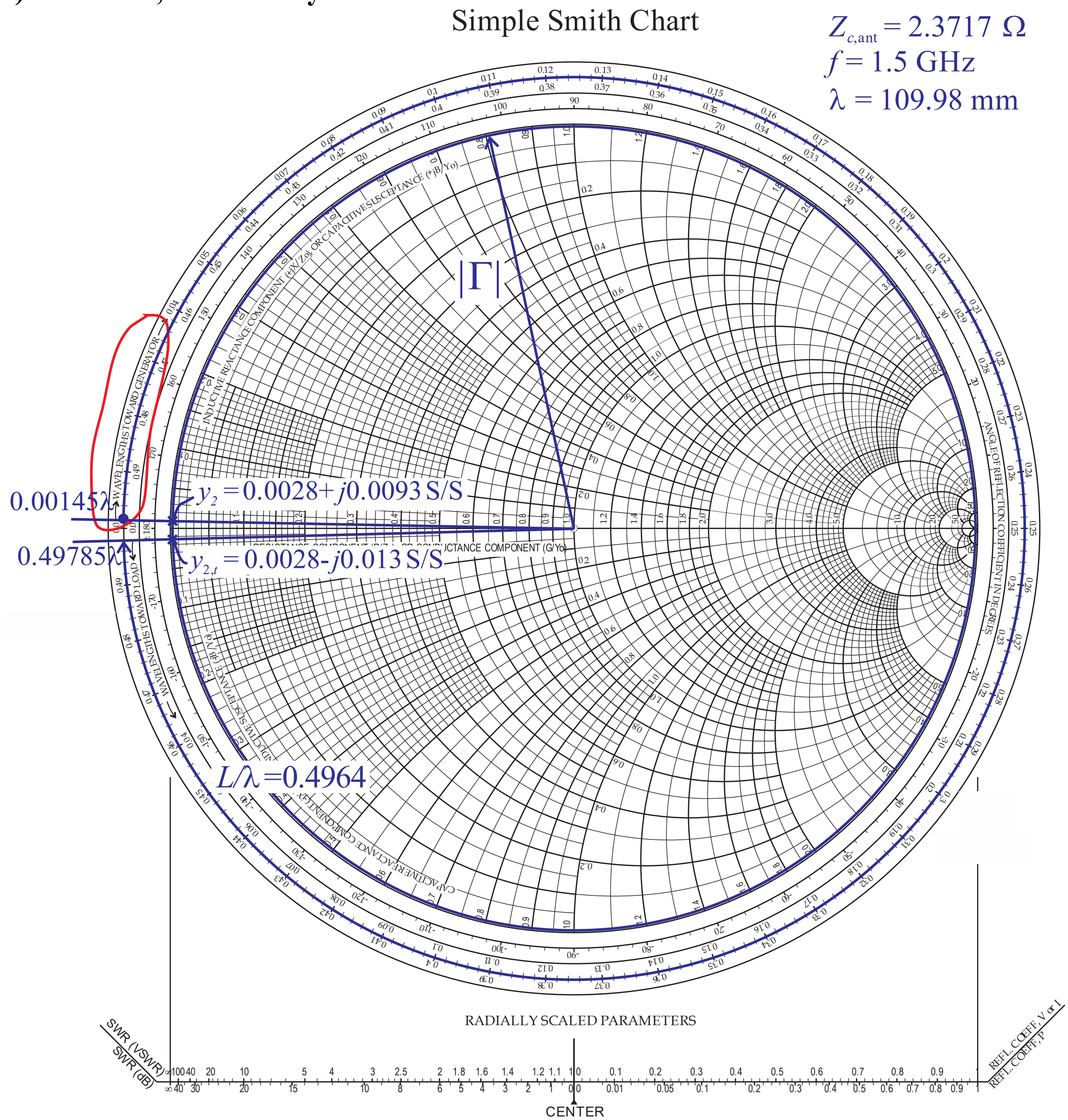
10) Numerically calculate the mutual conductance G_{12} (14-18a) between the slots

$$G_{12} = \frac{1}{\pi\eta_0} \int_{\theta=0}^{\pi} \left[\frac{\sin\left(\dfrac{k_0 W}{2}\cos\theta\right)}{\cos\theta}\right]^2 J_0\left(k_0 L\sin\theta\right)\sin^3\theta\, d\theta$$

$$= \frac{1}{\pi(376.73)} \int_{\theta=0}^{\pi} \left[\frac{\sin\left(\dfrac{31.44(0.0675)}{2}\cos\theta\right)}{\cos\theta}\right]^2 J_0\left(31.44(0.0542)\sin\theta\right)\sin^3\theta\, d\theta$$

$\Rightarrow$ $\underline{\mathbf{G_{12} = 0.5828\ mS}}$

9) continued, EE 583 only



11) Calculate R_{in}, use plus (+) sign in (14-17) equation.

$$Z_{\text{in}} = R_{\text{in}} = \frac{1}{2(G_1 + G_{12})} = \frac{1}{2(1.1798 + 0.5828)10^{-3}} \quad \Rightarrow \quad Z_{\text{in}} = R_{\text{in}} = 283.6752\ \Omega$$

12) Since an inset microstrip feed is required (i.e., $R_{in} \neq Z_{c,feed}$), calculate length y_0 of the inset needed to match the rectangular patch to the feeding transmission line. When $G_1/Y_{c,feed} << 1$ and $B_1/Y_{c,feed} << 1$, a good starting point is

$$y_0 \approx \frac{L}{\pi}\cos^{-1}\left(\sqrt{\frac{Z_{c,feed}}{R_{in}}}\right) \quad \text{(14-20a)}.$$

Here, $G_1/Y_{c,feed} = 0.0011798/0.02 = 0.059 << 1$ (OK),

but $B_1/Y_{c,feed} = 0.00393/0.02 = 0.197 << 1$ (so-so).

So, we will estimate $y_{0,est} \approx \frac{0.054203}{\pi}\cos^{-1}\left(\sqrt{\frac{50}{283.6752}}\right) \Rightarrow$ **$y_{0,est}$ = 19.63 mm**

Check this estimate using (14-20a)-

$$R_{in}(y_0) \simeq \frac{1}{2(G_1+G_{12})}\left[\cos^2\left(\frac{\pi y_0}{L}\right) + \frac{G_1^2+B_1^2}{Y_{c,feed}^2}\sin^2\left(\frac{\pi y_0}{L}\right) - \frac{B_1}{Y_{c,feed}}\sin\left(\frac{2\pi y_0}{L}\right)\right]$$

$$\simeq 283.675\left[\cos^2\left(\frac{\pi y_0}{0.0542}\right) + \frac{0.00118^2+0.00393^2}{0.02^2}\sin^2\left(\frac{\pi y_0}{0.0542}\right) - \frac{0.00393}{0.02}\sin\left(\frac{2\pi y_0}{0.0542}\right)\right]$$

$\Rightarrow$ **$R_{in}(y_{0,est}$ = 19.63 mm) = 17.348 Ω**

Since $R_{in}(y_{0,est})$ is too low, iteratively shorten inset length y_0 using above equation-

$\Rightarrow$ With **y_0 = 16.4786 mm**, $R_{in}(y_0) = 50\ \Omega = Z_{c,feed}$.

13) Determine the width W_0 of the feeding microstrip transmission line.

Method 2: Iteratively guess the width W_0 of the feeding transmission line using-

$$\varepsilon_{r,eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W_0}\right]^{-0.5} \quad \text{(14-1)}$$

and (14-19b)

$$Z_{c,feed} = \frac{\eta_0}{\sqrt{\varepsilon_{r,eff}}\left[\frac{W_0}{h}+1.393+0.667\ln\left(\frac{W_0}{h}+1.444\right)\right]} \qquad \frac{W_0}{h} > 1.$$

to get $Z_{c,feed} = 50\ \Omega$ and $\varepsilon_{r,eff} = 2.67$, when $W_0 = 2.331895\,h = 1.8958$ mm.

Using the Rogers Corporation Microwave Impedance Calculator (MWI 2018), W_0 = 1.883 mm. Assume Rogers know their boards best and choose $\Rightarrow$ **W_0 = 1.88 mm**.

14) Select the notch width n in the range $0.2W_0 < n < 0.5W_0$ (notes).

Arbitrarily select $n \approx 0.48W_0 \quad \Rightarrow \quad$ **$n = 0.9$ mm**.

15) Draw the resulting design.