ECE 3317
Applied Electromagnetic Waves

Final Exam

Dec. 7, 2023

Name: ____

General Information:

The exam is open-book and open-notes. You are not allowed to use any device that has communication functionality (laptop, cell phone, ipad, etc.).

Instructions:

- Show all of your work. No credit will be given if the work required to obtain the solutions is not shown.
- Write neatly. You will not be given credit for work that is not easily legible.
- Leave answers in terms of the parameters given in the problem.
- Show units in all of your final answers.
- Circle your final answers.
- Double-check your answers. For simpler problems, partial credit may not be given.
- If you have any questions, ask the instructor. You will not be given credit for work that is based on a wrong assumption.
- Make sure you sign the academic honesty statement below.

Academic Honesty Statement

By taking this exam, you agree to abide by the UH Academic Honesty Policy during this exam. You understand and agree that the punishment for violating this policy will be most severe, including getting an F in the class and getting expelled from the University.

Signature: ____

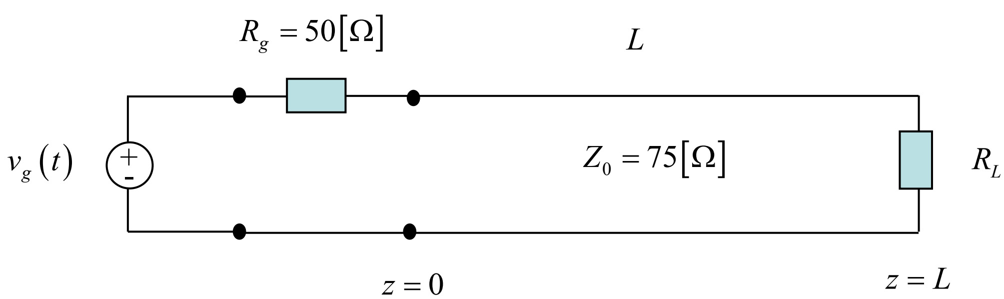
Problem 1 (25 pts)

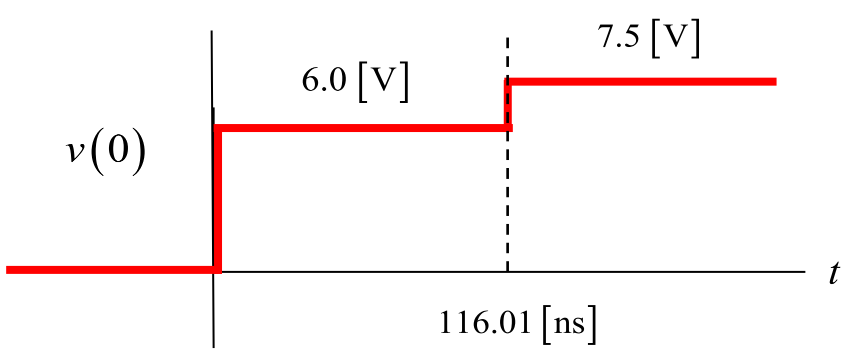
A TDR (time-domain reflectometer) has a generator voltage $v_g(t)$ that is a step function with an amplitude of V_0 volts. The TDR has a 50 [Ω] Thévenin impedance. The TDR is connected to a transmission line with a characteristic impedance of 75 [Ω]. At the end of the line there is a load R_L. The transmission line is a coax that has a Teflon filling (with a relative permittivity of 2.1). The TDR records the total voltage $v(0)$ at $z = 0$, and this is shown in the plot below.

(a) What is the length of the line L in meters?

(b) What is the amplitude V_0 of the step function $v_g(t)$?

(c) What is the load resistance R_L?





SOLUTION

Part (a)

The speed of the signal is the velocity of light in the dielectric. We have

$$c_d = \frac{c}{\sqrt{\varepsilon_r}} = 2.06876 \times 10^8 \left[\text{m/s}\right].$$

The length of the line is related to the time t_d that the change in the voltage is recorded by the TDR.

$$2L = c_d t_d .$$

Solving for L we have

$$L = 12.000 \left[\text{m}\right].$$

Part (b)

From the voltage divider equation we have

$$V^+ = V_0 \left(\frac{Z_0}{R_g + Z_0} \right).$$

Hence,

$$6.0 = V_0 \left(\frac{75}{50+75} \right).$$

This gives us

$$V_0 = 10 \left[\text{V}\right].$$

Part (c)

We have

$$V^+ \left(1 + \Gamma_L + \Gamma_L \Gamma_g \right) = 7.5 \left[\text{V}\right].$$

Hence, we have

$$6.0\left(1+\Gamma_L+\Gamma_L\left(-0.2\right)\right)=7.5\ [\mathrm{V}]$$

or

$$6.0\left(1+\Gamma_L\left(0.8\right)\right)=7.5\ [\mathrm{V}]$$

or

$$\Gamma_L = 0.3125.$$

We also have

$$\Gamma_L = \frac{R_L - Z_0}{R_L + Z_0} = \frac{R_L - 75}{R_L + 75}.$$

Hence,

$$\frac{R_L - 75}{R_L + 75} = 0.3125.$$

This gives us

$$R_L = 143.18\ [\Omega].$$

Problem 2 (25 pts)

A device (load) on a printed circuit board has an input impedance of $Z_L = 100 + j50$ [Ω]. We want to match the load to an incoming 50 [Ω] microstrip feed line. To do this we put an open-circuited stub in parallel with the main feed line at a distance $d = 0.15\lambda_g$ from the load. The stub has a length of l_s and also has a characteristic impedance of 50 [Ω]. A quarter-wave transformer is then placed at a distance of $\lambda_g / 2$ from the stub.

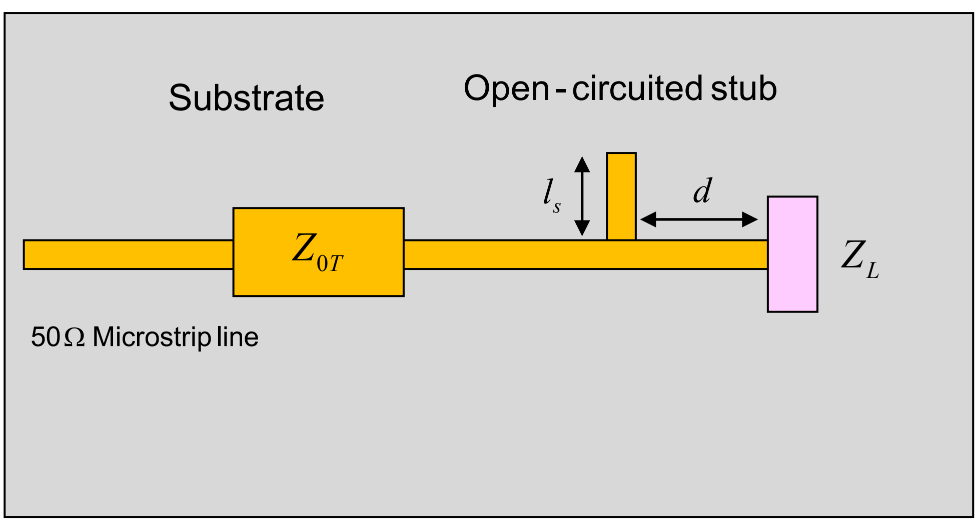
The frequency is 5 [GHz] and the relative effective permittivity of the microstrip lines is 1.75.

a) What is the normalized input admittance just to the right of the stub? Use the first Smith chart on the next pages.

b) Design the stub length l_s in terms of λ_g. Use the second Smith chart on the next pages.

c) Find the value of λ_g in mm.

d) Find value of the transformer characteristic impedance Z_{0T}.



SOLUTION

Part (a)

From the first Smith chart we have

$Y_{in}^{N} = 0.65 + j(0.65)$.

Part (b)

From the second Smith chart we have

$l_s = 0.408\lambda_g$.

Part (c)

We have

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r^{\text{eff}}}}.$$

This gives us

$\lambda_g = 45.324\ [\text{mm}]$.

Part (d)

At a point just to the right of the stub, the normalized input admittance (from the first smith chart) is 0.65. The normalized impedance is then 1 / 0.65 = 1.54. Unnormalized, this corresponds to 76.9 [Ω].

We the have

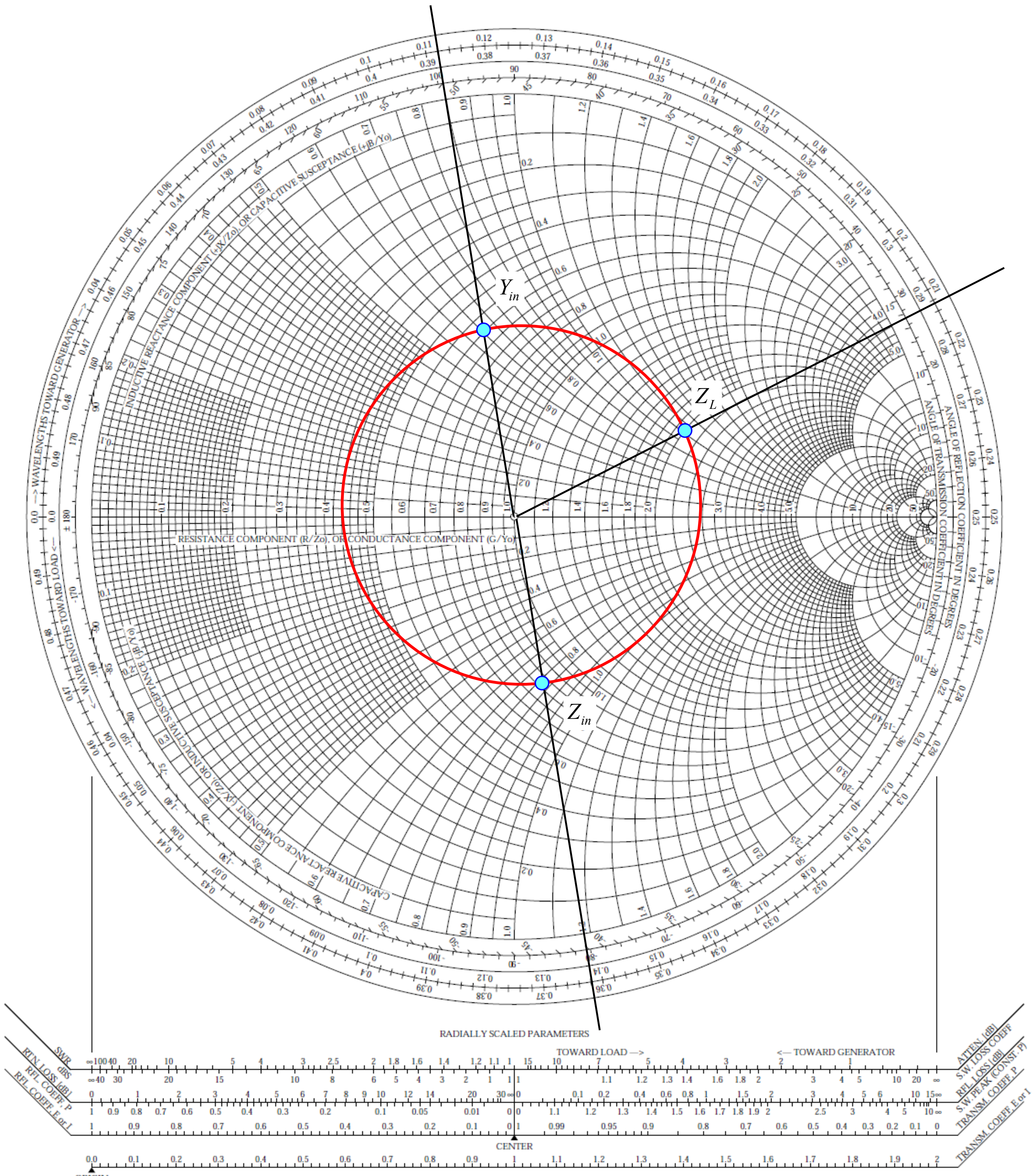
$$Z_{0\text{T}} = \sqrt{(50)(76.9)}.$$

Hence,

$Z_{0\text{T}} = 62.0\ [\Omega]$.

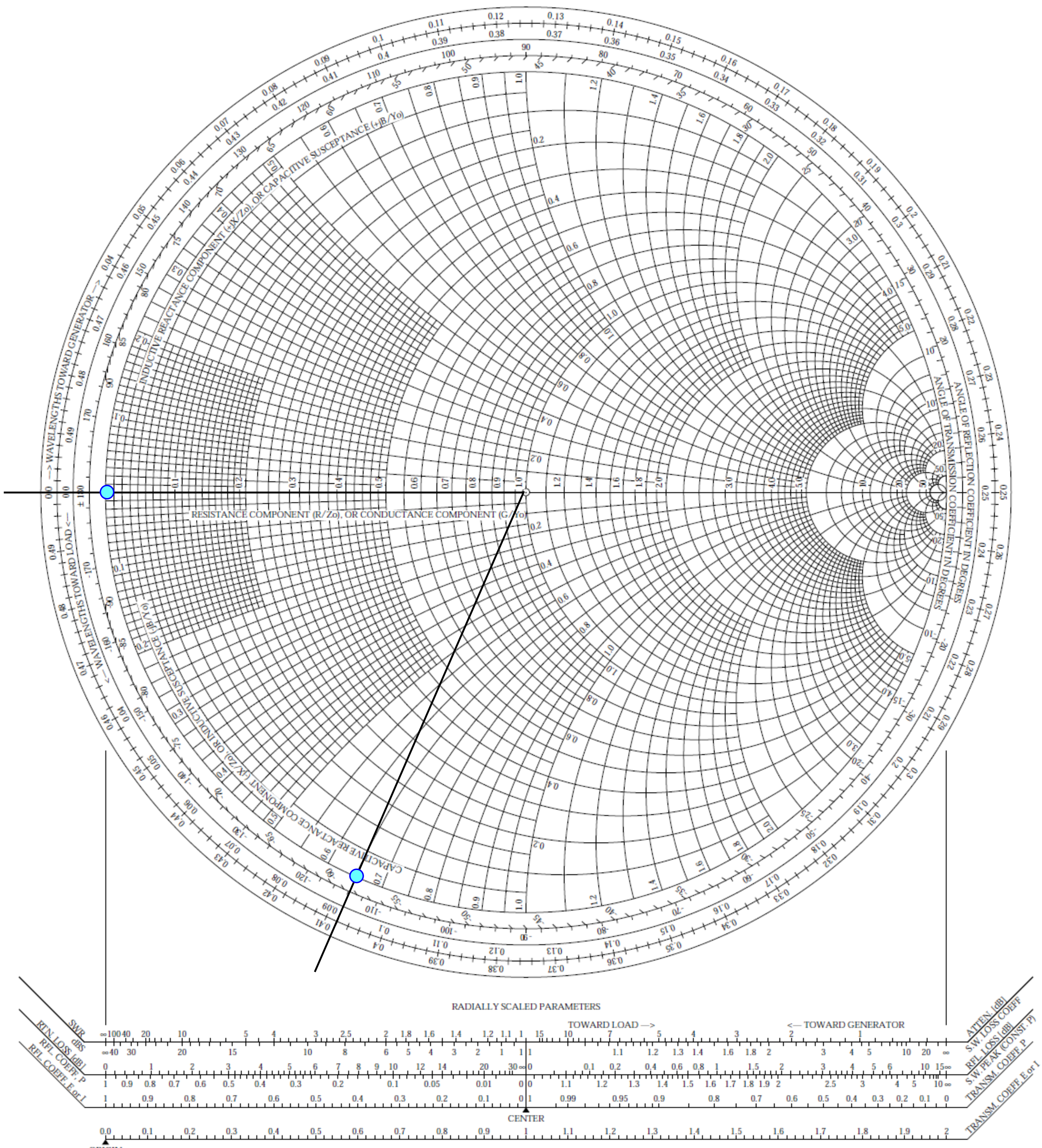
The Complete Smith Chart

Black Magic Design



The Complete Smith Chart

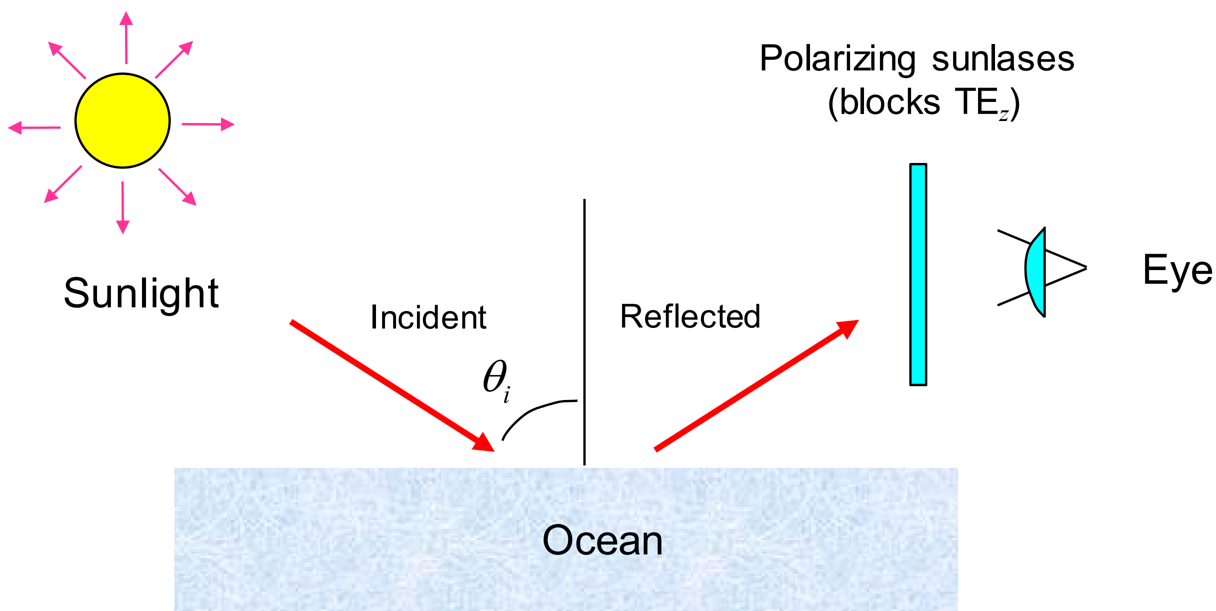
Black Magic Design



Problem 3 (25 pts)

Sunlight is incident on the ocean, which at optical frequencies is assumed to be lossless (and nonmagnetic) with a relative permittivity of 1.7689. The sunlight is randomly polarized, so that it has equal power densities in the TM_z and TE_z parts. The incident angle θ_i is 60°. The sunlight reflects off of the ocean and then goes through polarizing sunglasses to reach a person's eyes. The polarizing sunglasses allow the TM_z polarization to go through, but they block the TE_z polarization.

Find the percentage of the incident power density that makes it through the sunglasses, after reflecting off the ocean.



SOLUTION

Part (a)

The transmitted angle is, from Snell's law,

$$\theta_t = 0.70909\ [\text{radians}] = 40.628^\circ .$$

Only the TM reflected wave makes it thought the sunglasses. Therefore, the percent power that makes it through the sunglasses is (assuming the incident power density is 1.0 [W/m^2])

$$P_r^{\%} = 100\left(\frac{1}{2}\left|\Gamma_{\text{TM}}\right|^2\right).$$

We have

$$\Gamma_{\text{TM}} = \frac{Z_2^{\text{TM}} - Z_1^{\text{TM}}}{Z_2^{\text{TM}} + Z_1^{\text{TM}}}$$

$$Z_1^{\text{TM}} = \frac{k_{z1}}{\omega\varepsilon_1} = \frac{k_1\cos\theta_i}{\omega\varepsilon_0} = \frac{k_0\cos\theta_i}{\omega\varepsilon_0} = \eta_0\cos\theta_i = (376.7303)\cos\left(60^\circ\right) = 188.37\ [\Omega]$$

$$Z_2^{\text{TM}} = \frac{k_{z2}}{\omega\varepsilon_2} = \frac{k_2\cos\theta_t}{\omega\varepsilon_0\varepsilon_r} = \frac{k_0\sqrt{\varepsilon_r}\cos\theta_t}{\omega\varepsilon_0\varepsilon_r} = \frac{\eta_0}{\sqrt{\varepsilon_r}}\cos\theta_t = \left(\frac{376.7303}{\sqrt{1.7689}}\right)\cos\left(40.628^\circ\right) = 215.00\ [\Omega].$$

This gives us

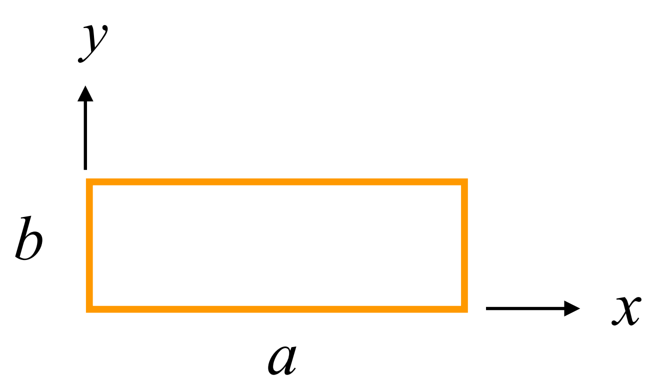
$$\Gamma_{\text{TM}} = \frac{Z_2^{\text{TM}} - Z_1^{\text{TM}}}{Z_2^{\text{TM}} + Z_1^{\text{TM}}} = \frac{26.630}{403.37} = 0.0660$$

$$P_r^{\%} = 0.217.$$

Problem 4 (25 pts)

a) Design the dimensions a and b of an air-filled rectangular waveguide that is to be used for transmission of electromagnetic power at 6.0 [GHz]. This frequency should be at the center of the operating frequency band, which is the frequency band over which only the TE_{10} mode can propagate. Choose the height b of the waveguide so that it can carry maximum power without sacrificing the bandwidth of the operating frequency band.

b) Find the power in watts that the waveguide can carry at 6.0 [GHz] if the magnitude of the electric field inside the waveguide is not allowed to exceed a value of $E_c = 3.0 \times 10^6$ [V/m] (the breakdown field strength of air at normal atmospheric pressure).



SOLUTION

Part (a)

The design frequency should be halfway between the cutoff frequencies of the TE_{10} mode and the TE_{20} mode, since $b = a/2$. Therefore, we have

$$f_0 = 1.5 f_c^{10} = 1.5\left(\frac{c}{2a}\right).$$

This gives us

$$a = 3.7474 \ [\text{cm}].$$

We then have

$$b = 1.8737 \ [\text{cm}].$$

Note that

$$f_c^{10} = 4.0 \ [\text{GHz}].$$

Part (b)

We use

$$P_z = \left(\frac{ab}{4\omega\mu_0}\right)\beta\left|E_{10}\right|^2.$$

We set $\left|E_{10}\right| = 3.0\times10^6 \ [\text{V/m}]$.

We also have

$$\beta = \frac{2\pi}{\lambda_g} = \frac{2\pi}{\lambda_0}\sqrt{1-\left(\frac{f_c^{10}}{f_0}\right)^2} = 93.729 \ [\text{radians/m}].$$

We then have

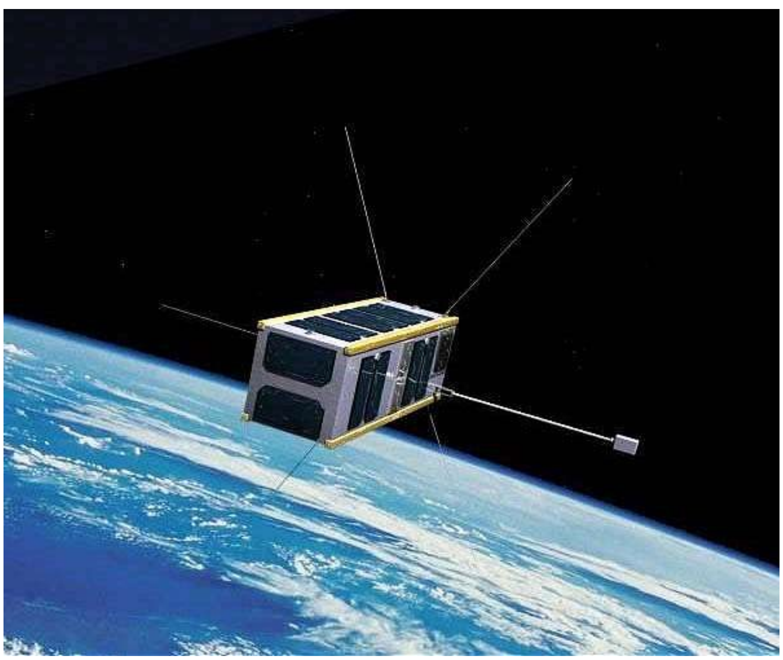
$$P_z = 3.1257\times10^6 [\text{W}] = 3.1257 [\text{MW}].$$

Bonus Problem (20 pts)

A CubeSat satellite orbits the Earth as shown below. It radiates at 3.0 GHz with 2 [W] of power that is input to a dipole antenna that has a gain of $G = 1.5$. A student on earth receives the signal from the CubeSat using a Yagi antenna that has a gain of $G = 30$. The receive antenna (the Yagi) has an input impedance of 50 [Ω] and is connected to a receiver that is modeled as a 50 [Ω] load. The CubeSat is at an altitude of 350 [km]. Both antennas may be assumed to be lossless.

a) Calculate the power received by the receiver circuit that is connected to the Yagi antenna.

b) Calculate the magnitude of the open-circuit (Thévenin) signal voltage of the Yagi antenna.



A CubeSat orbiting the Earth.

SOLUTION

Part (a)

The power received is

$$P_{\text{rec}} = \left[\left(\frac{P_{\text{in}}}{4\pi r^2}\right)G_{\text{trans}}\right]A_e^{\text{rec}}$$
$$= \left[\left(\frac{P_{\text{in}}}{4\pi r^2}\right)G_{\text{trans}}\right]\left[G_{\text{rec}}\left(\frac{\lambda_0^2}{4\pi}\right)\right].$$

Inserting the numbers, we have

$$P_{\text{rec}} = \left[\left(\frac{2}{4\pi\left(3.5\times 10^5\right)^2}\right)1.5\right]\left[30\left(\frac{(0.099931)^2}{4\pi}\right)\right].$$

This gives us

$$P_{\text{rec}} = 4.6461\times 10^{-14} \ [\text{W}].$$

Part (b)

We have

$$P_{\text{rec}} = \frac{|V_{\text{Th}}/2|^2}{2R_L} = \frac{|V_{\text{Th}}/2|^2}{2(50)} = |V_{\text{Th}}|^2(0.0025000).$$

This gives us

$$|V_{\text{Th}}|^2(0.0025000) = 4.6461\times 10^{-14}$$

so that

$$|V_{\text{Th}}| = 4.3110\times 10^{-6} \ [\text{V}] = 4.3110 \ [\mu\text{V}].$$